12th International Planetary Probe Workshop – Short Course 'Radio Flyers'
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Radar in Planetary Exploration

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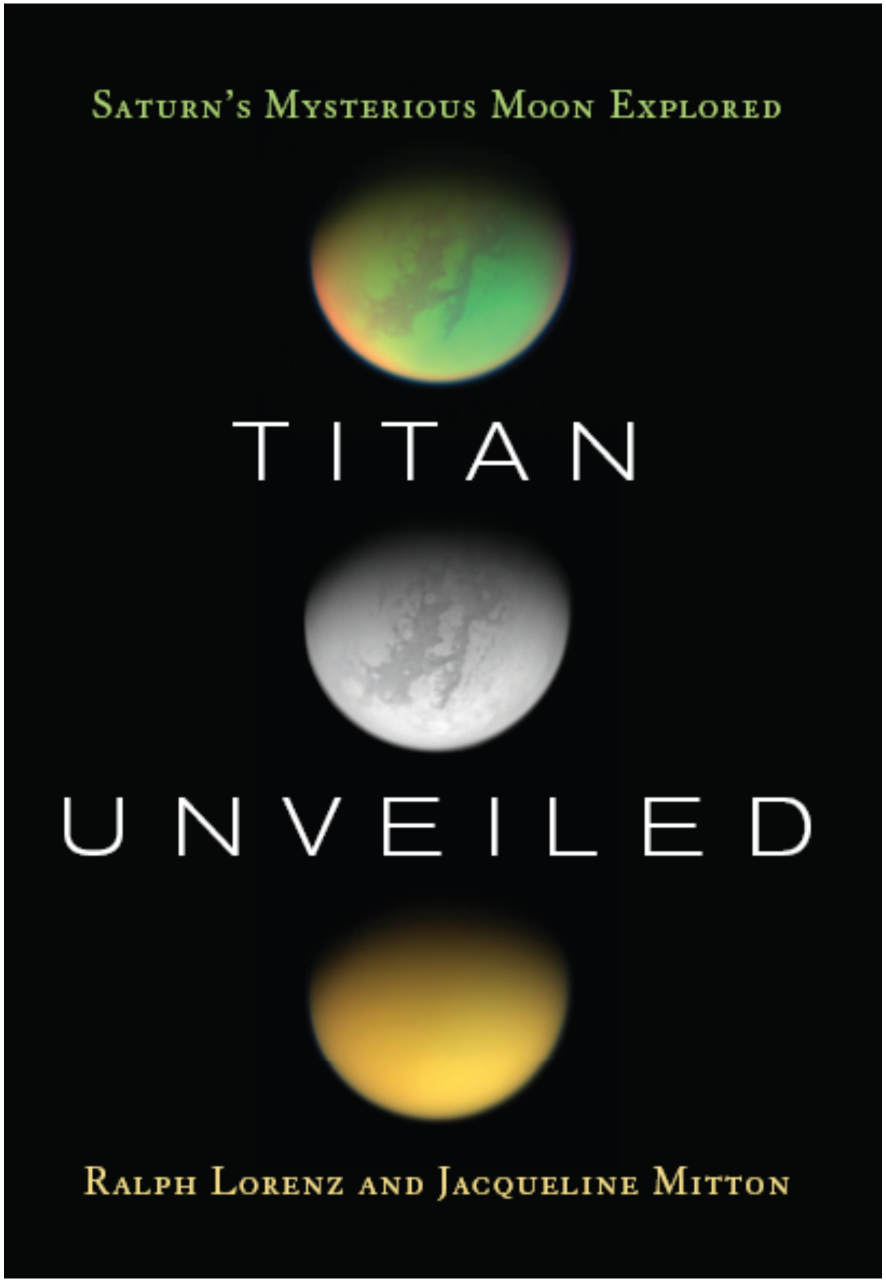
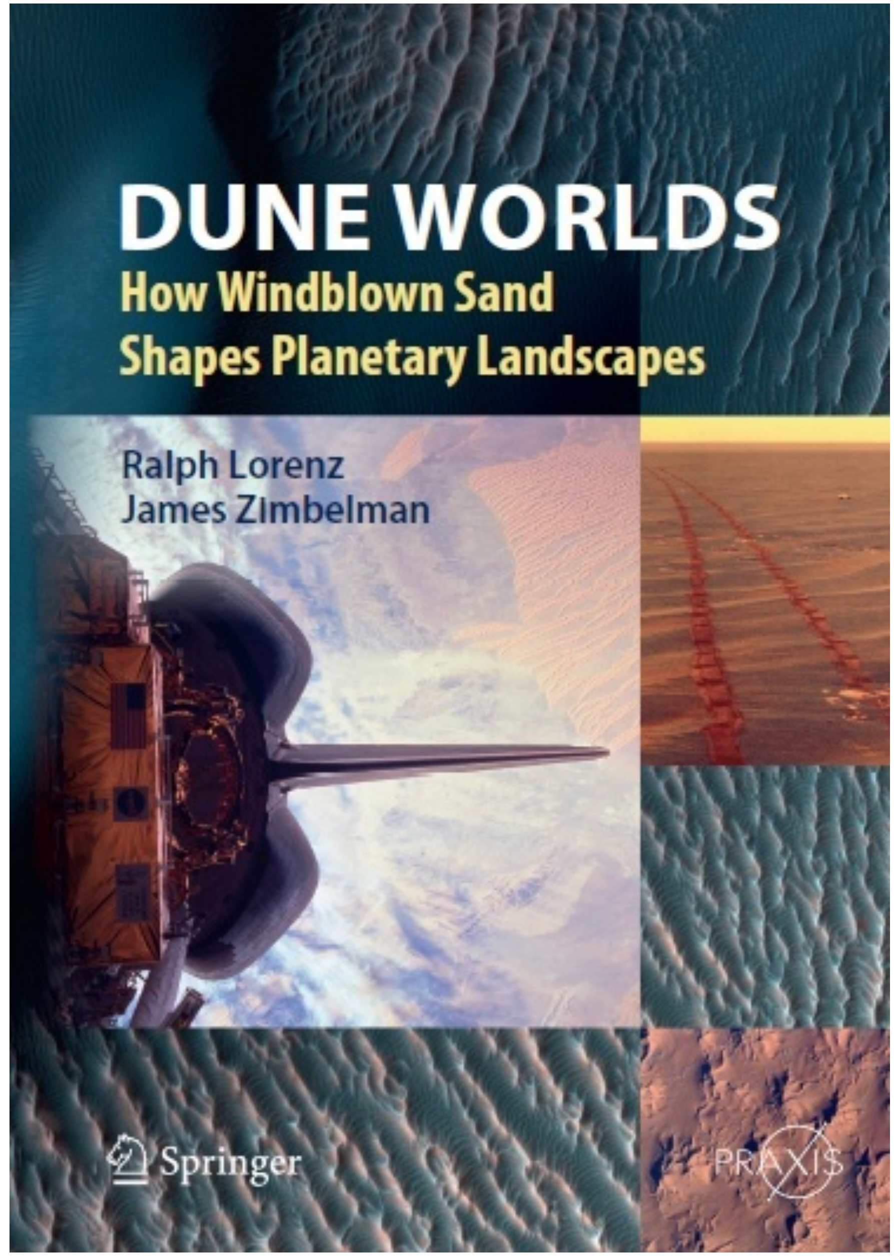
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY



PUP 2008 (2010)



Springer, 2014

Basic Principles : Types, Antennas, Signal Processing

Altimeters

Pioneer Venus, Magellan, Cassini

Sounding Radars

Apollo, Kaguya, MARSIS, SHARAD

Imaging Radars

Magellan, Cassini, Mini-RF / Mini-SAR

Ground-Penetrating Radar

(EM propagation Apollo, Rosetta-Consert) Yutu

Future

Mars 2020 (Rimfax), JUICE / Europa (RIME / REASON)

Venus, Mars ?

RADAR - some words...

Send a known radio signal, receive the echo. Simple.

CW - continuous wave, constant frequency. Means there is no timing information, but there is range-rate information (Speed trap, baseball etc.)

Pulse - short pulse, measure echo transit time. Provides a range measurement. (but short pulse means wide frequency range and high instantaneous power)

Various compromises introduced ('pulse-doppler' , 'FMCW' , chirp waveform) to allow efficient extraction of desired information, both range and range-rate.

If precision measurement of reflectivity is of interest (sea state - winds) instrument is called a 'scatterometer'. If the range precision is of interest, an 'altimeter' ; if the radiation goes deep into target, a 'sounder'

In the scenario where the spacecraft is moving relative to the planet, range rate maps to surface position and with processing one can develop an image - Synthetic Aperture Radar (SAR). (Or sometimes the object moves - Inverse SAR, as in groundbased imaging of asteroids)

Wavelength is a critical parameter

(HF >10 m; VHF ~m ; UHF, L-band – 10s of cm; S, X , Ku – 12, 3, 2cm; Ka ~mm)
10s of MHz ; >100MHz ; 400MHz, 1.4GHz ; 2, 8, 14 GHz ; 30 GHz)

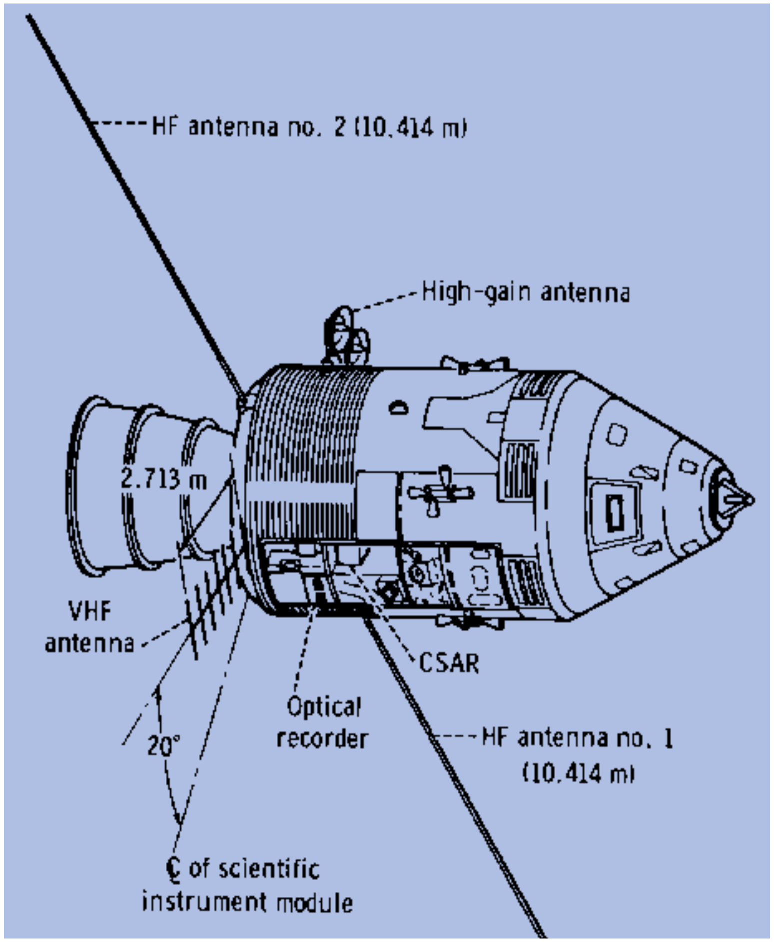
Determines the size of antenna needed for a given beamwidth
Also determines penetration of radiation into surface material (longer wavelengths go deeper)

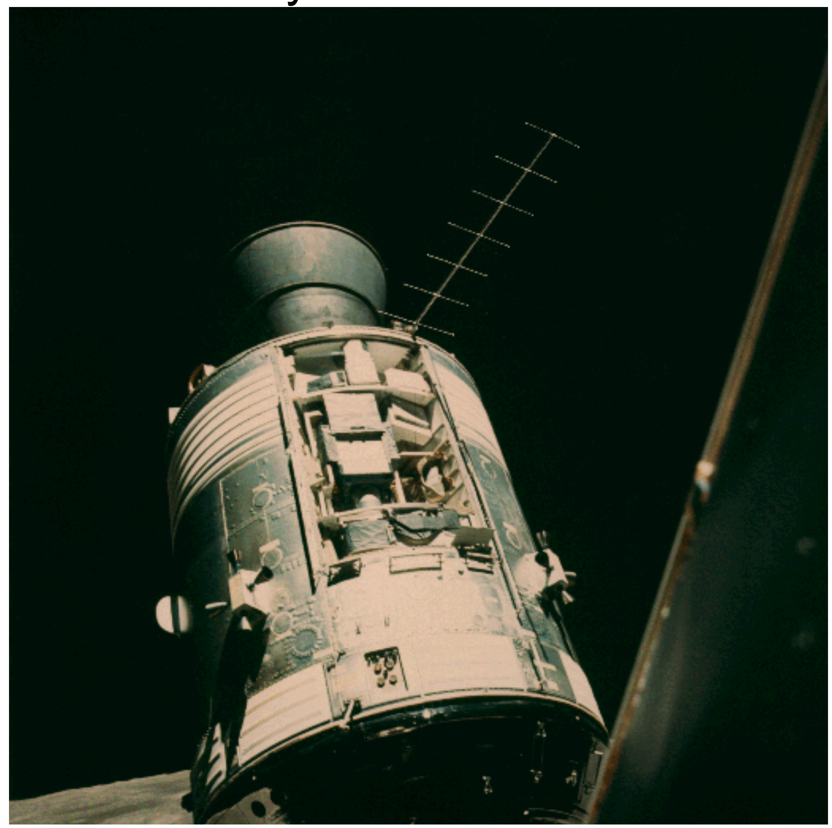
Atmospheric absorption - Ka band attenuated by Titan atmosphere ; Venus atmosphere absorbs Ka and X band.

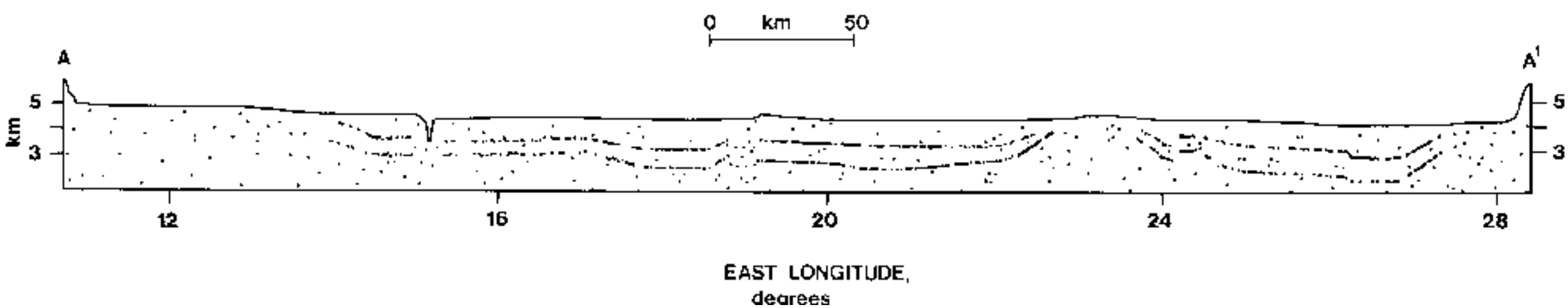
Technology improvements allow higher power at progressively higher frequency

Radar measurements are often coherent – exact path length (in fractions of a wavelength) strongly affects return. Images often 'speckly'. Allows interferometric methods.

ALSE (Apollo Lunar Radar Sounder)
Apollo 17 - 5, 15 and 150 MHz with dipole and yagi antenna. Optical Data acquisition ! Some detections of layers in Mare basalt







Kaguya (Selene) Lunar Radar Sounder 2007-2009

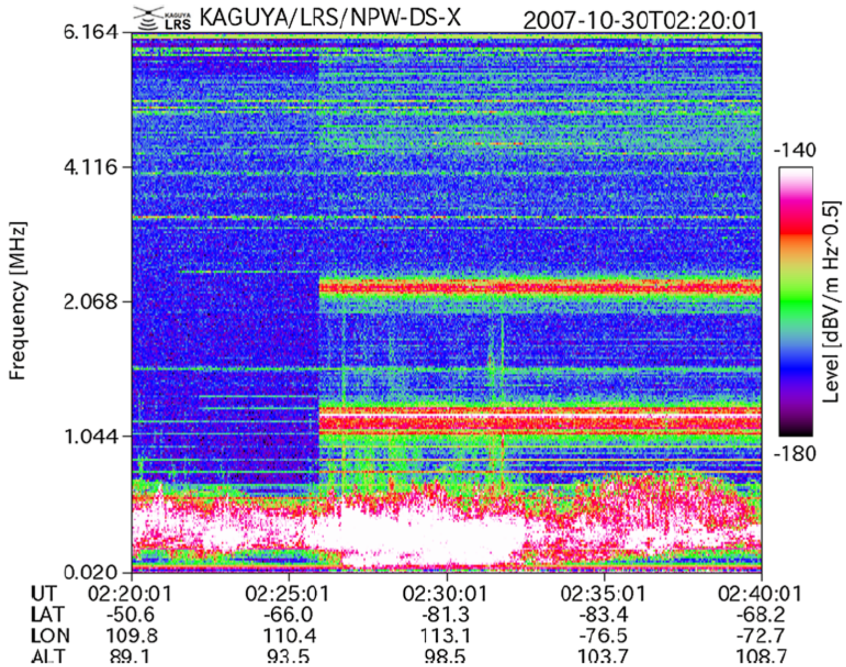
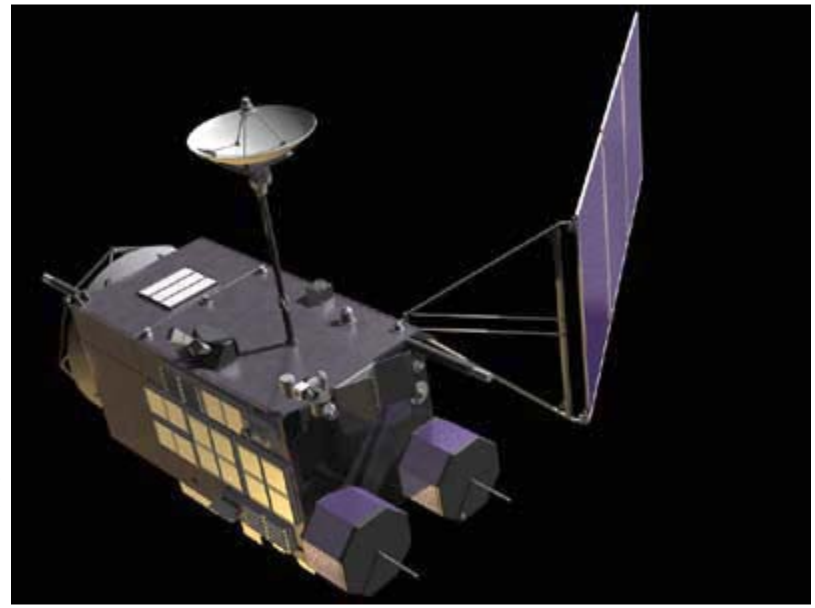
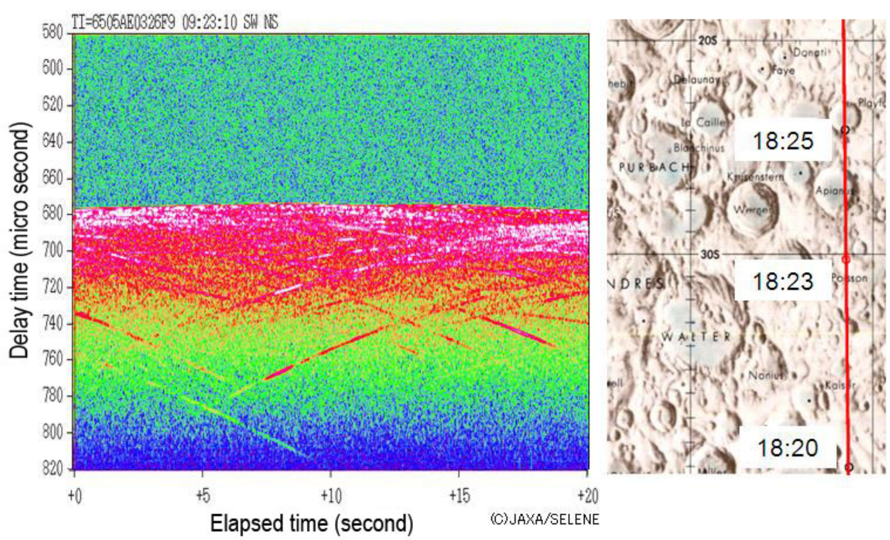
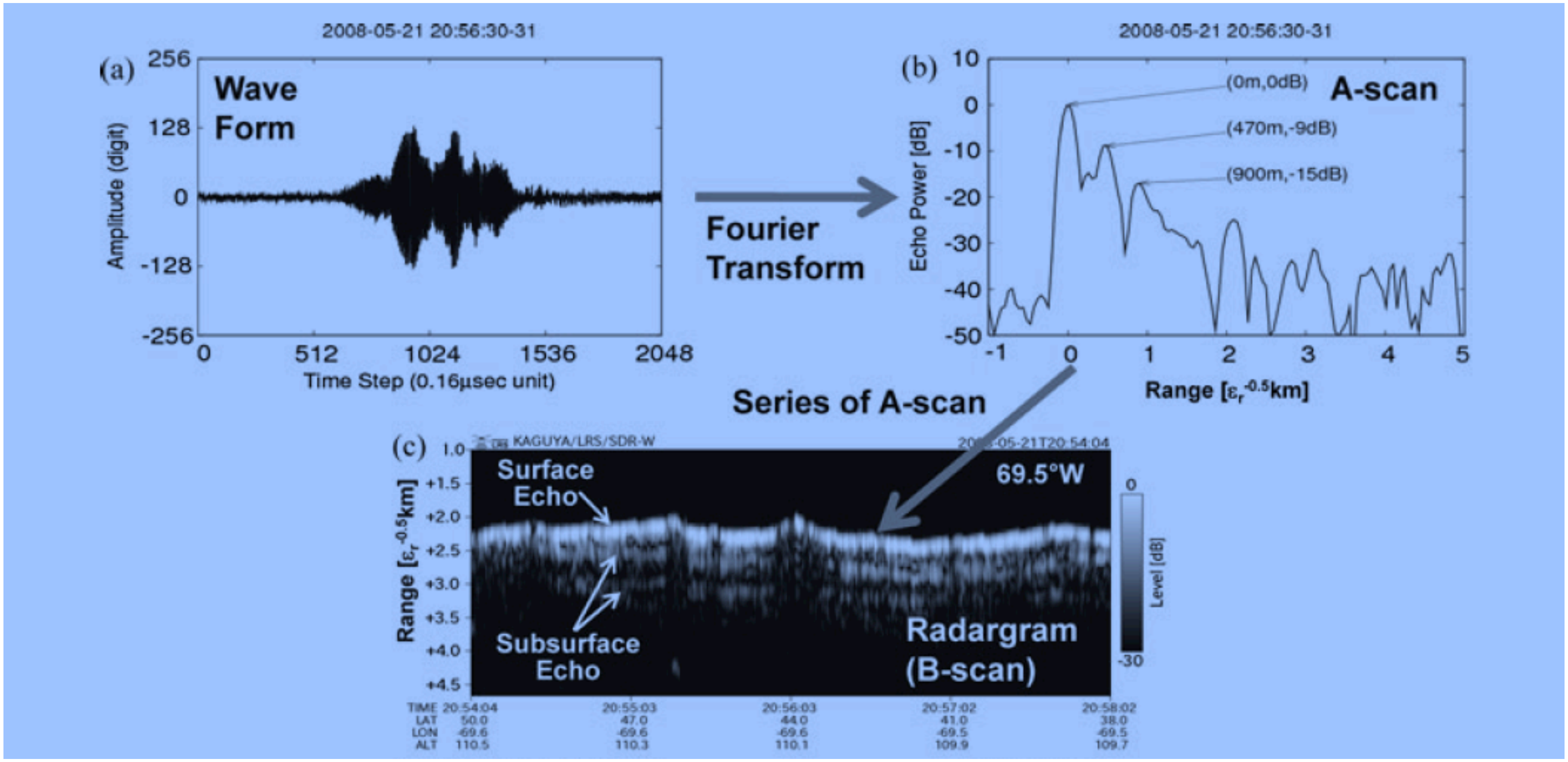


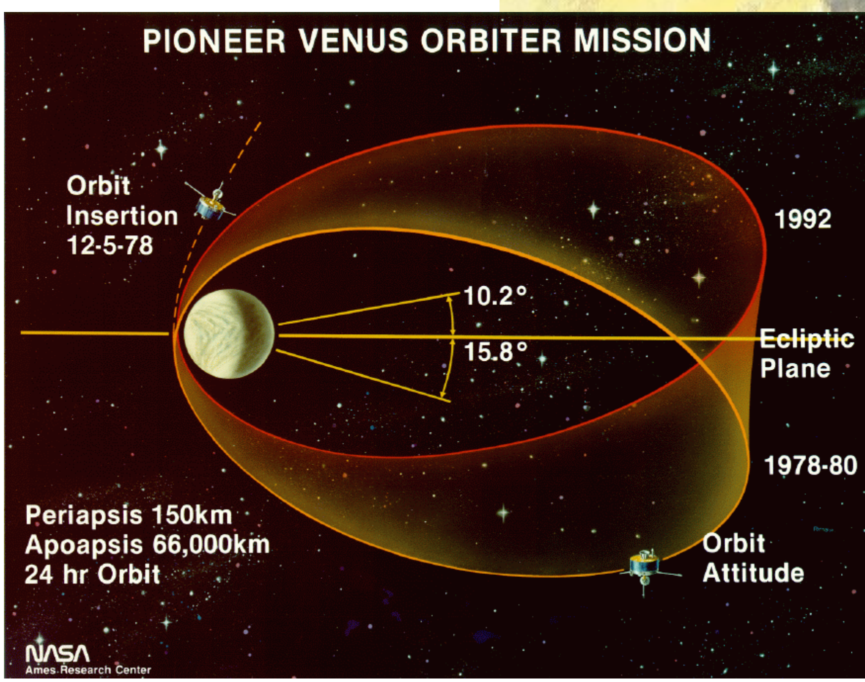
Fig. 16 The spacecraft power supply noises at about 1 MH and 2 MHz. Frequency steps are linearly allocated between the labels. The noises occur when the spacecraft moves into the dayside. The background noise level also increases with several dB in wide frequency range. The emissions below 700 kHz are AKR



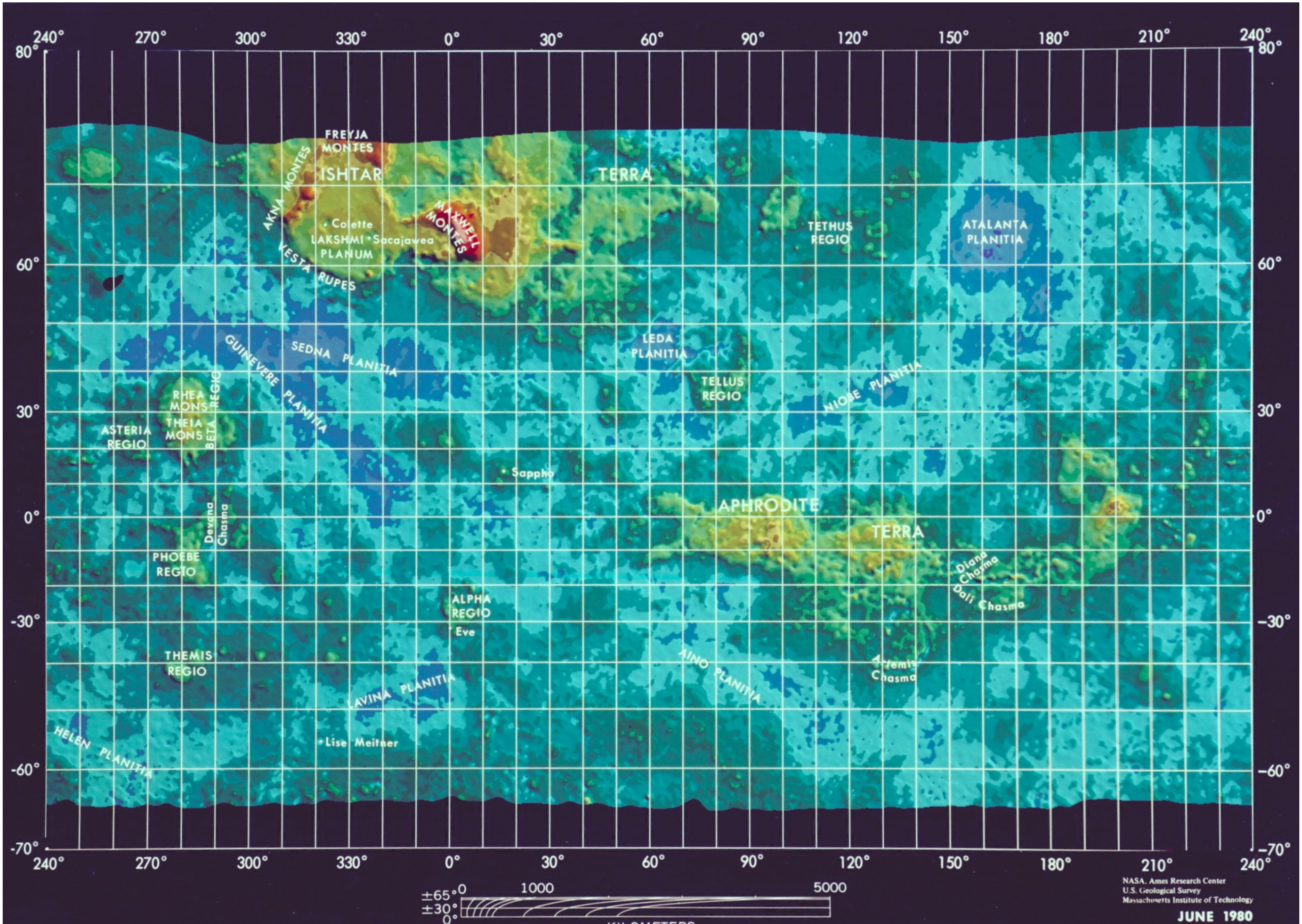


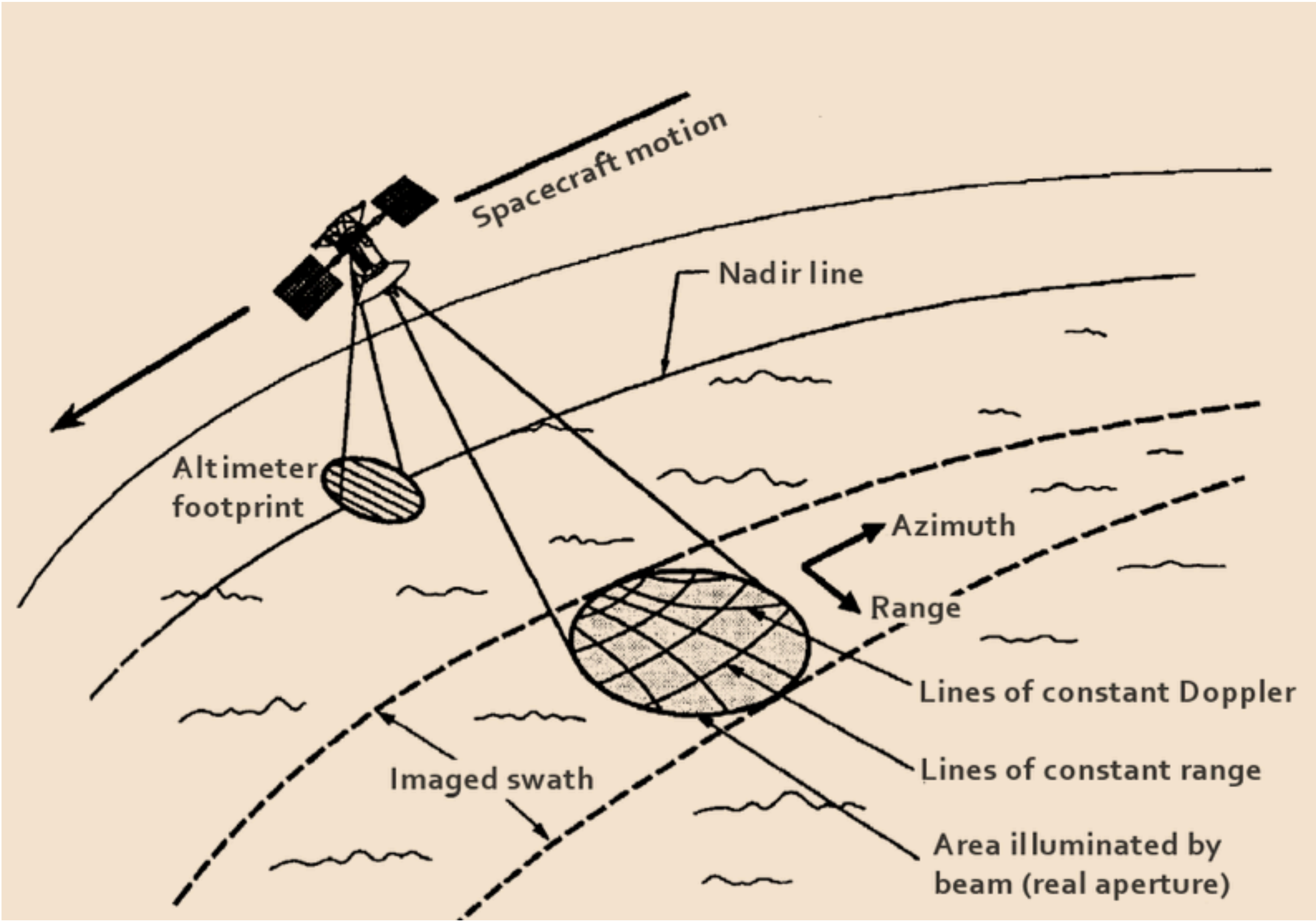


2008-05-21 20:56:30-31
(a)
Wave Form
Amplitude (digit)
Time Step (0.16µsec unit)
Fourier Transform
2008-05-21 20:56:30-31
(b)
A-scan
(0m,0dB)
(470m,-9dB)
(900m,-15dB)
Echo Power [dB]
Range [εr-0.5km]
Series of A-scan
(c)
KAGUYA/LRS/SDR-W
Surface Echo
69.5°W
Subsurface Echo
Radargram (B-scan)
Range [εr-0.5km]
Level [dB]



PIONEER VENUS ORBITER MISSION
Orbit Insertion 12-5-78
1992
10.2°
15.8°
Ecliptic Plane
1978-80
Periapsis 150km
Apoapsis 66,000km
24 hr Orbit
Orbit Attitude
NASA
Ames Research Center

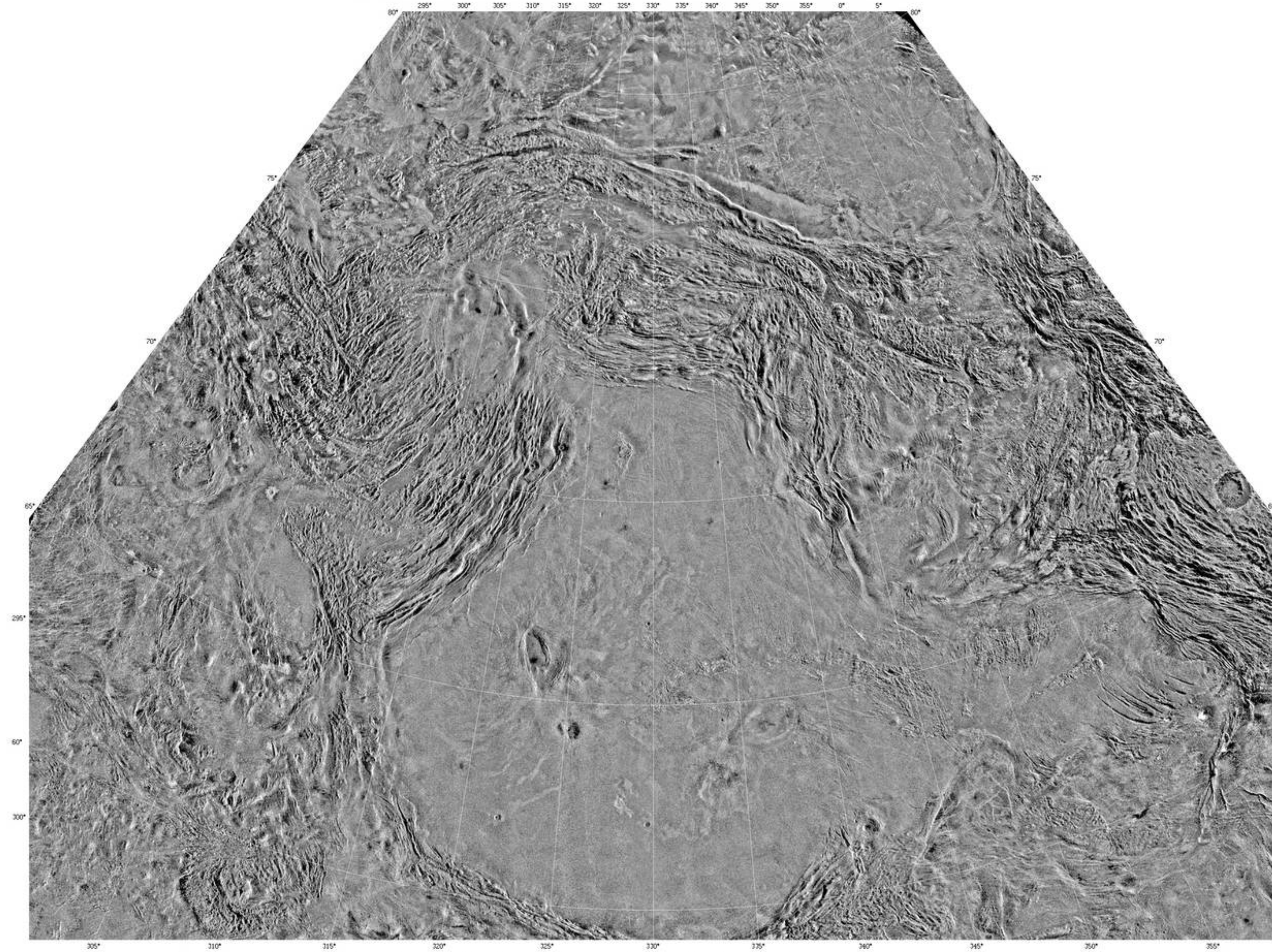

FREYJA MONTES
ISHTAR
TERRA
AKNA MONTES
MAXWELL MONTES
Colette
LAKSHMI PLANUM
Sacajawea
VESTA RUPES
TETHUS REGIO
ATALANTA PLANITIA
LEDA PLANITIA
SEDNA PLANITIA
GUINEVERE PLANITIA
TELLUS REGIO
NIOBE PLANITIA
RHEA MONS
THEIA MONS
BETA REGIO
ASTERIA REGIO
Sappho
APHRODITE
TERRA
Devana Chasma
PHOEBE REGIO
Diana Chasma
Dali Chasma
ALPHA REGIO
Eve
THEMIS REGIO
AINO PLANITIA
Artemis Chasma
LAVINA PLANITIA
Lise Meitner
HELEN PLANITIA
0 1000 5000
±65°
±30°
0°
KILOMETERS
NASA, Ames Research Center
U.S. Geological Survey
Massachusetts Institute of Technology
JUNE 1980
VENUS



Altimetry can be Doppler-sharpened along-track. Side-looking returns can be mapped in range and doppler to synthesize resolution much smaller than real aperture.

Venera 15 / 16.   1-2km Resolution. 8cm coded CW radar.   ~25% coverage

ВЕНЕРА ЗЕМЛЯ ИШТАР ПЛАТО ЛАКШМИ



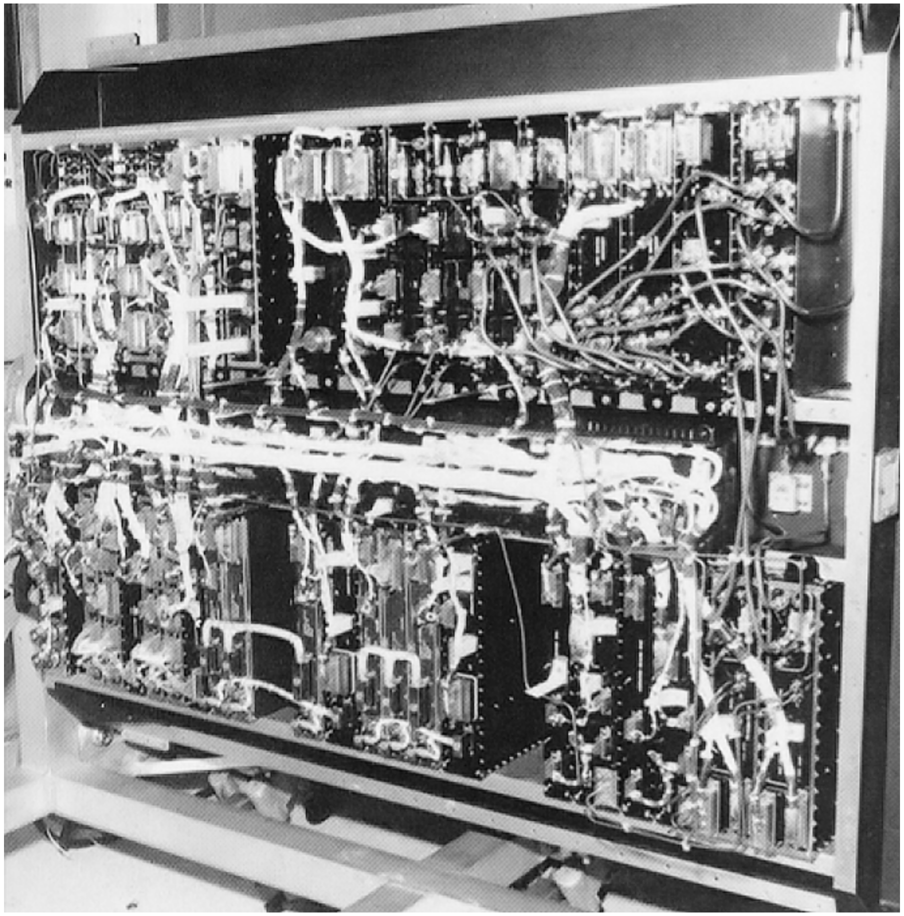
ФОТОКАРТА. ПРОЕКЦИЯ НОРМАЛЬНАЯ РАВНОУГОЛЬНАЯ КОНИЧЕСКАЯ ЛАМБЕРТА – ГАУССА. СТАНДАРТНЫЕ ПАРАЛЛЕЛИ 63.3° И 77.5°.

0 100 200 КМ

In the early 1990s, Magellan sent back more data than all previous planetary missions put together.....

Used S-band (NB Venus' atmosphere is thick enough to appreciably attenuate X-band)

Voyager spare HGA for SAR ; Horn antenna for altimetry

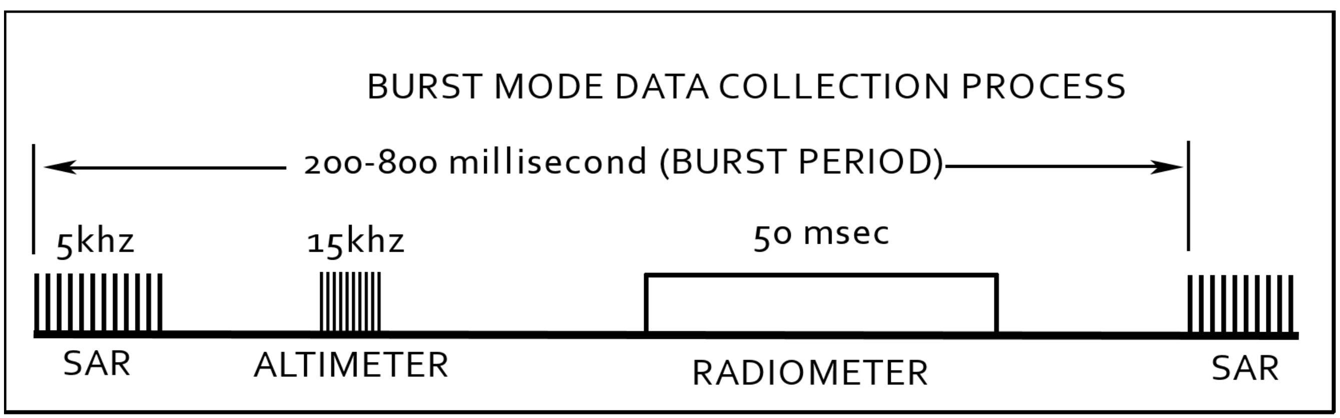


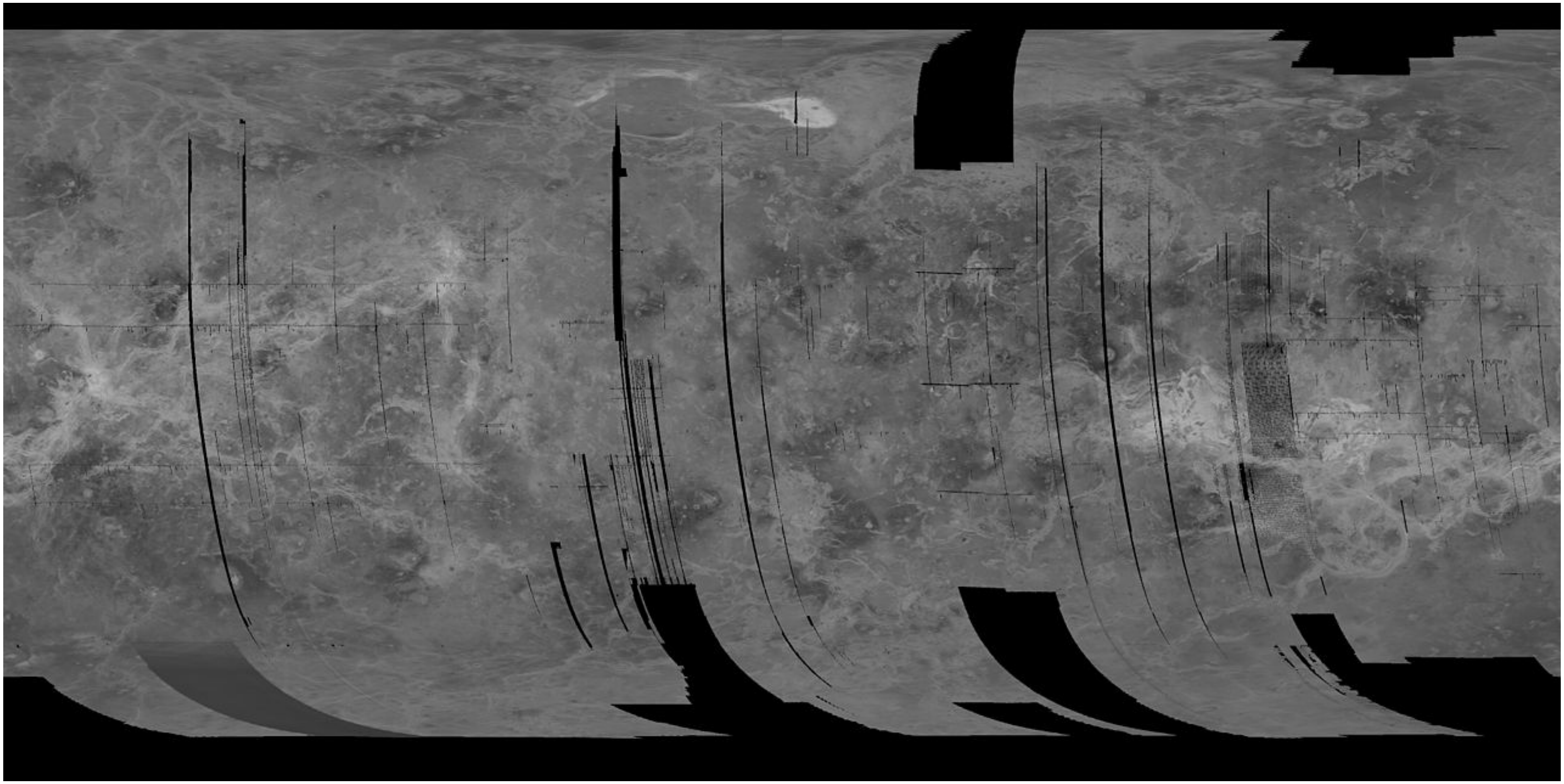
Lots of functions in a radar : chirp generation, amplification, timing, receiver, data compression, etc.

Timing is fn(altitude, look angle) – usually varies rapidly in planetary missions

Originally implemented in discrete logic (big, power-hungry, complicated).

But nowadays much of these functions are implemented via firmware/software



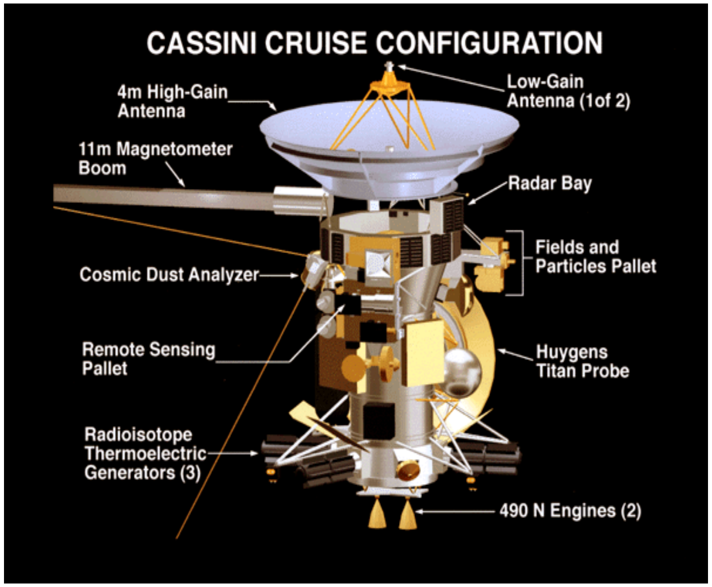


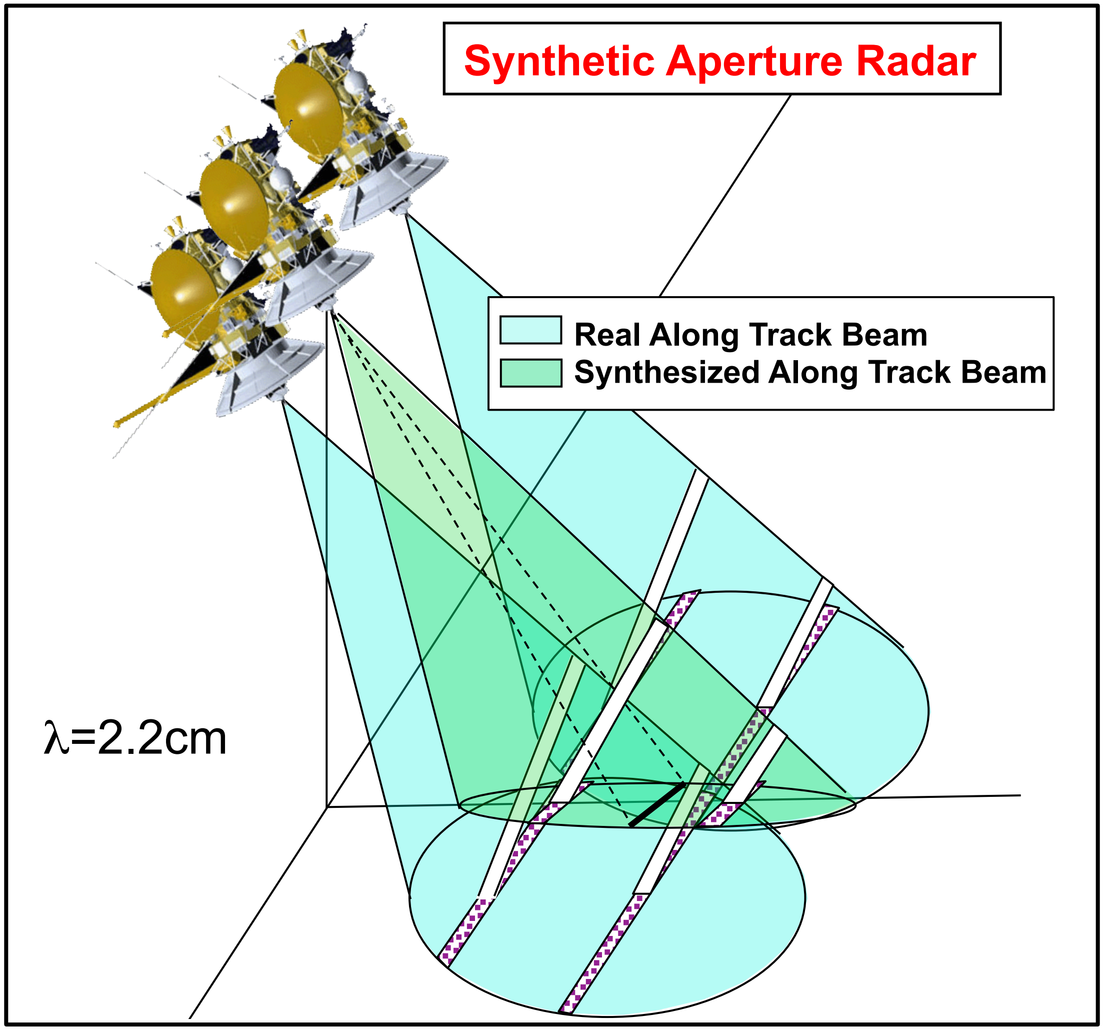
Cycle 1 Mapping Coverage (left look)
Also global altimetric map (uncontrolled) and radiometer map

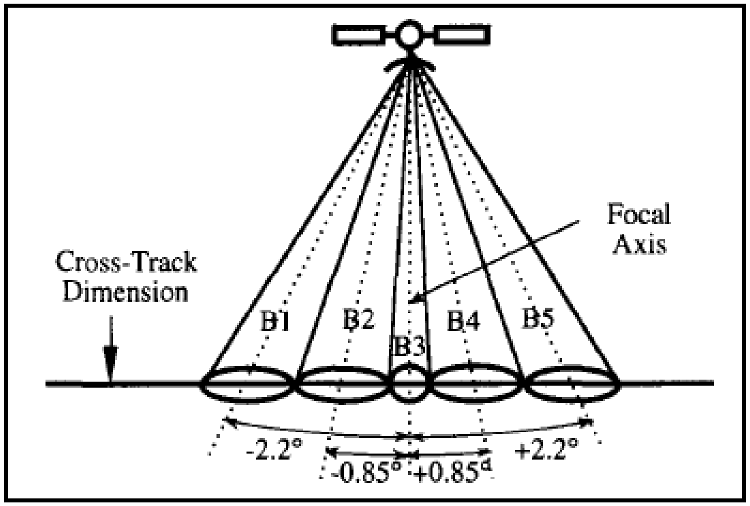
SAR image variable resolution   ~120m near equator , rather poorer near poles.

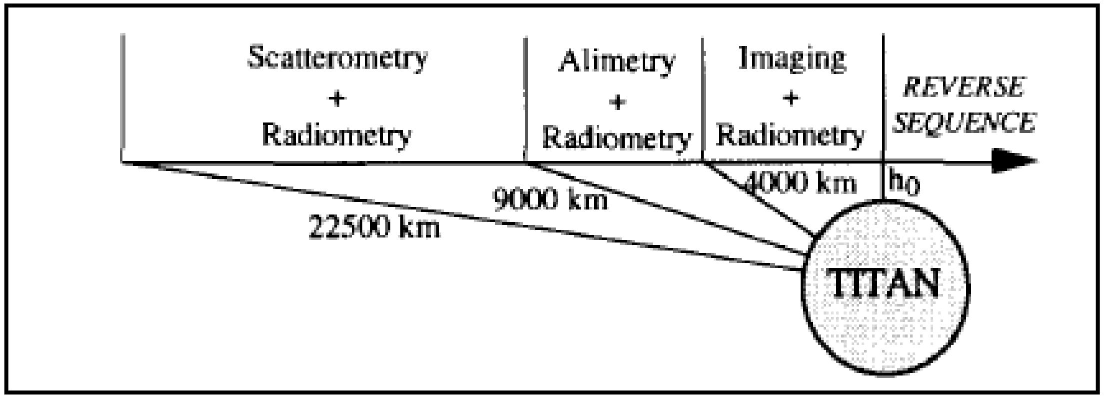
Radar stereo data acquired over much of Venus, not fully exploited.

Cassini RADAR

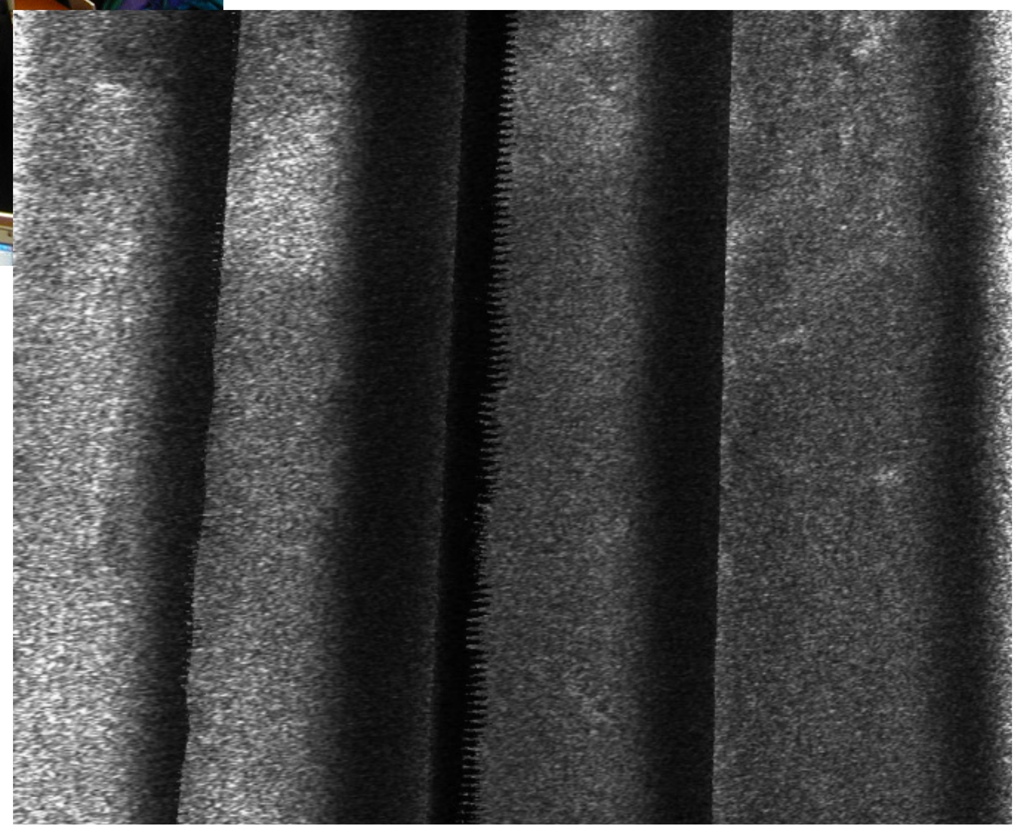








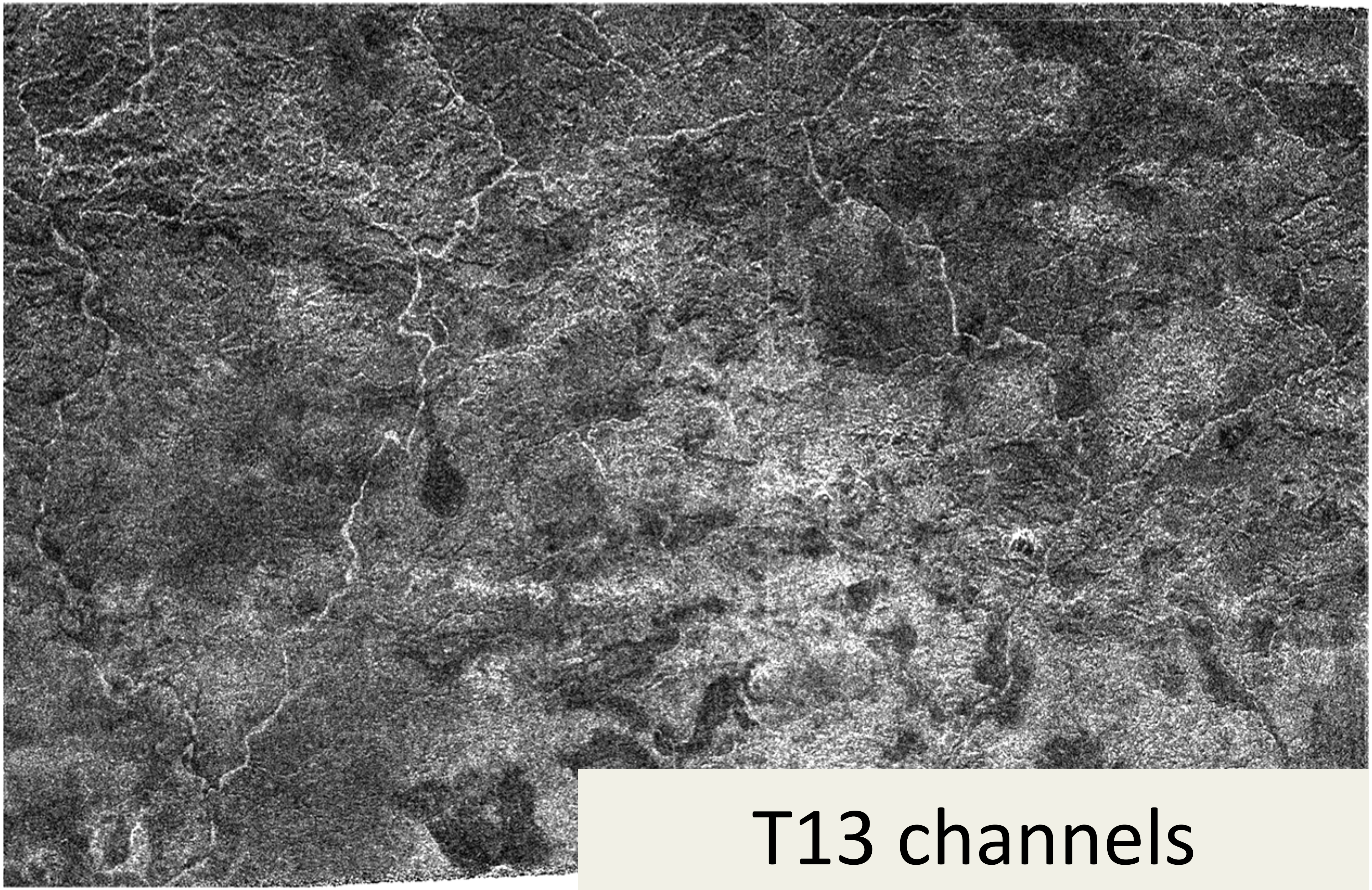
First Contact
TA October 2004
JPL



First run of the SAR processor - ugly (seams), but promising – there were features there ! (no prior imaging data)

Tuned up with different ephemeris an hour later, looked much better, but baffling

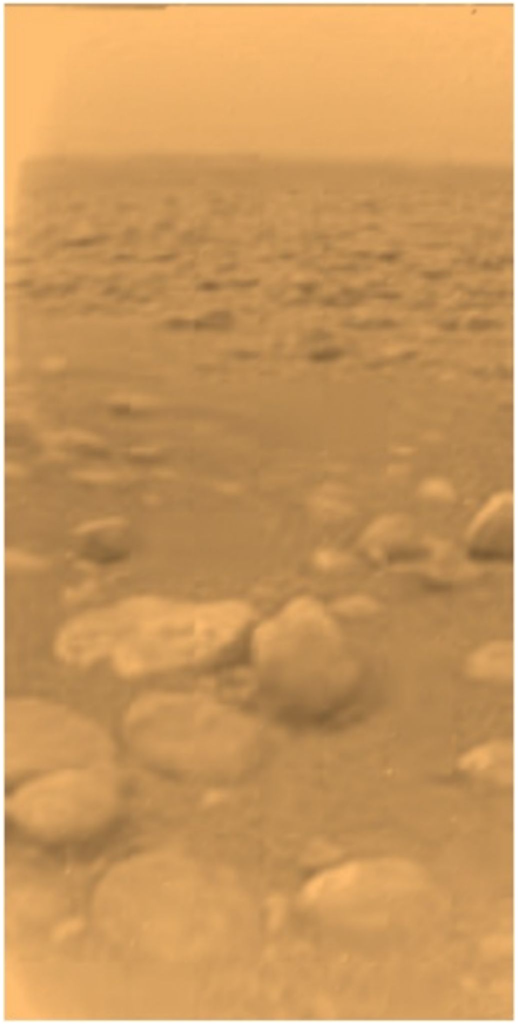
First external presentation – DPS, Louisville KY. Swaths exceeded standard poster space ! (Also, 32768 line image exceeded capabilities of early Photoshop versions)

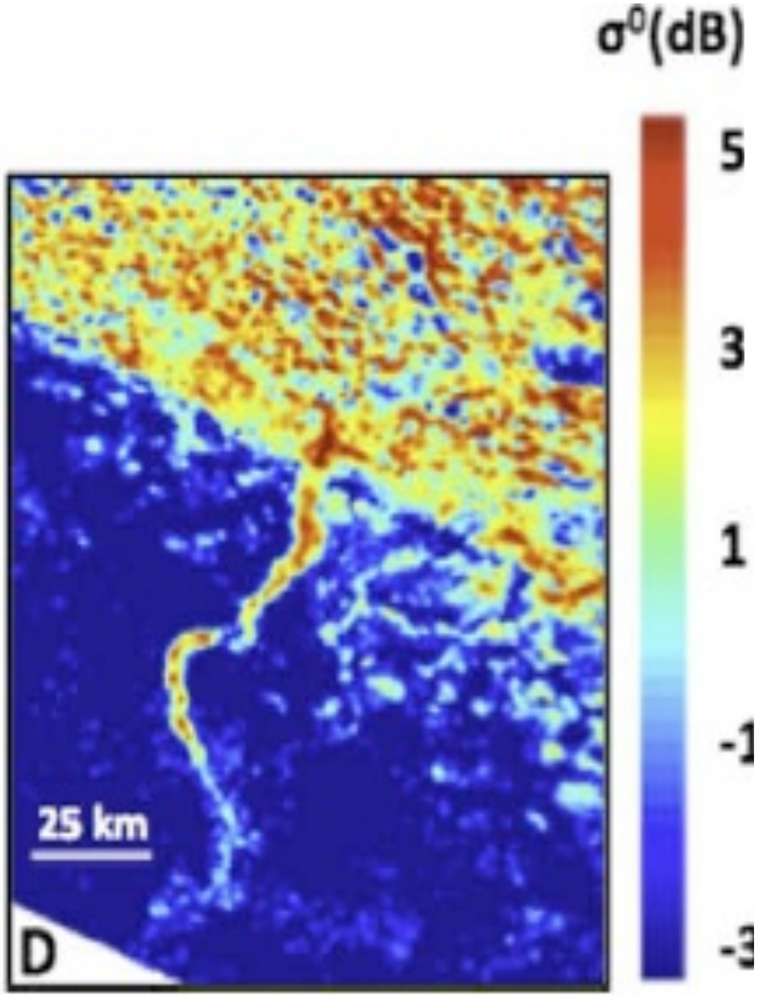


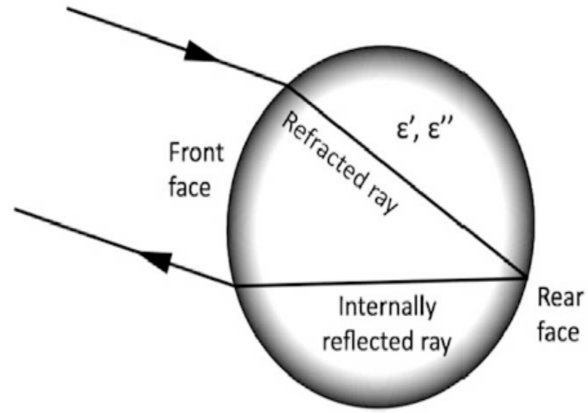
T13 channels

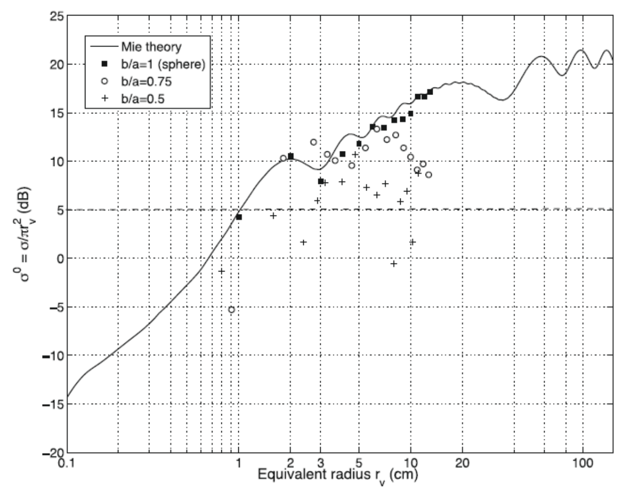
Radar-bright channels on Titan

A. Le Gall[a,*], M.A. Janssen[a], P. Paillou[b], R.D. Lorenz[c], S.D. Wall[a], the Cassini Radar Team

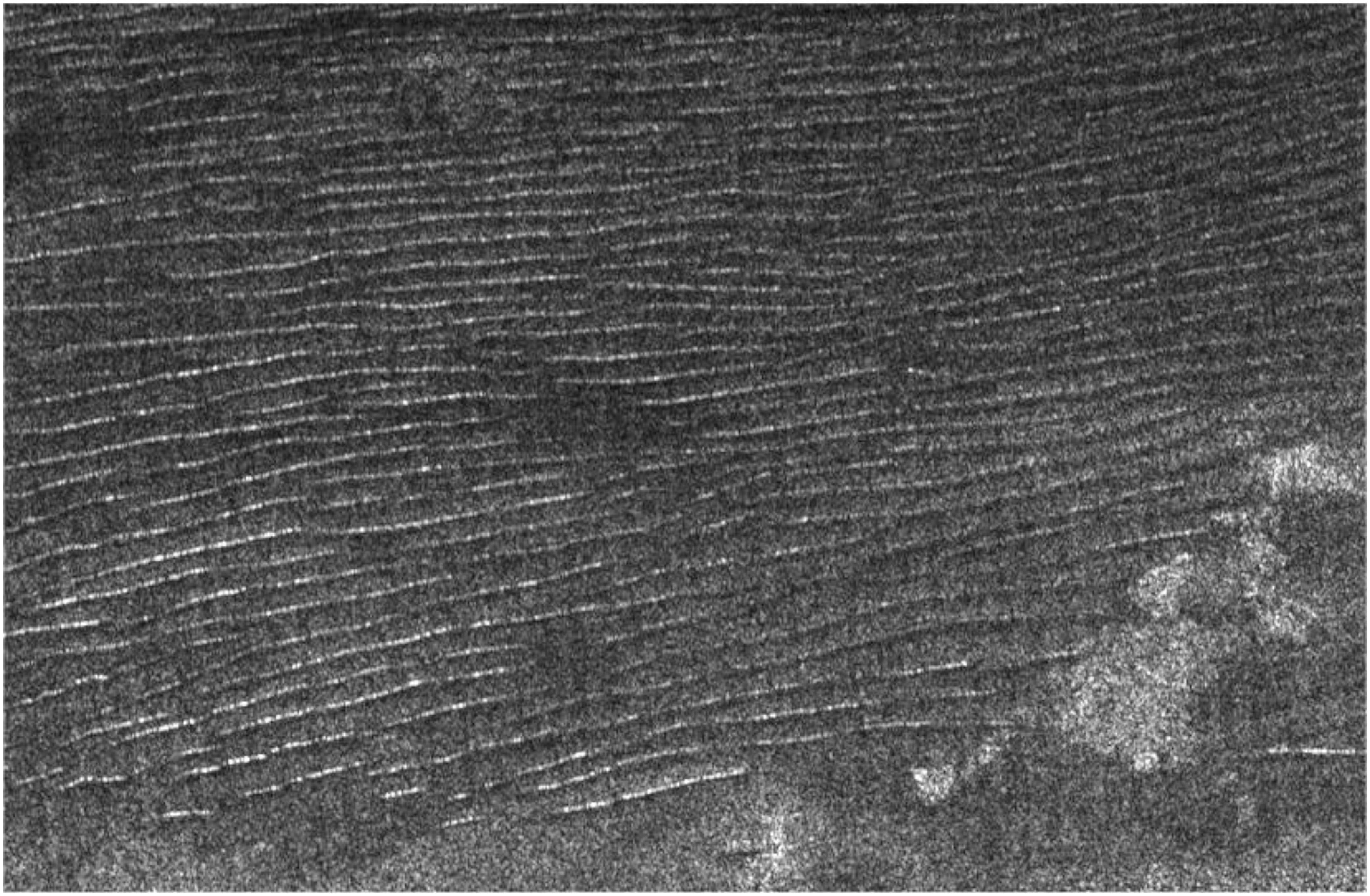




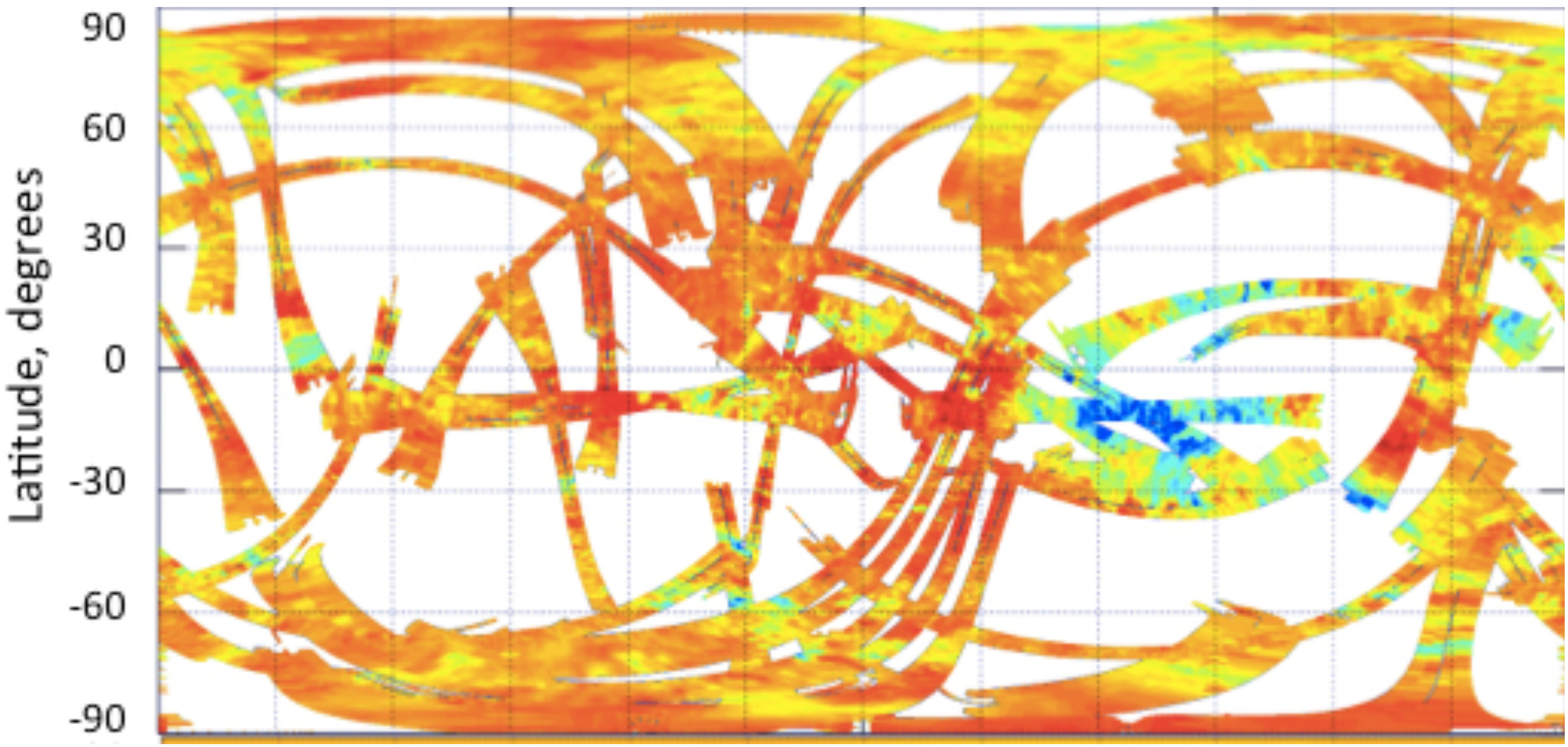




Belet and Shangri-La, W of Xanadu, covered in linear dunes.

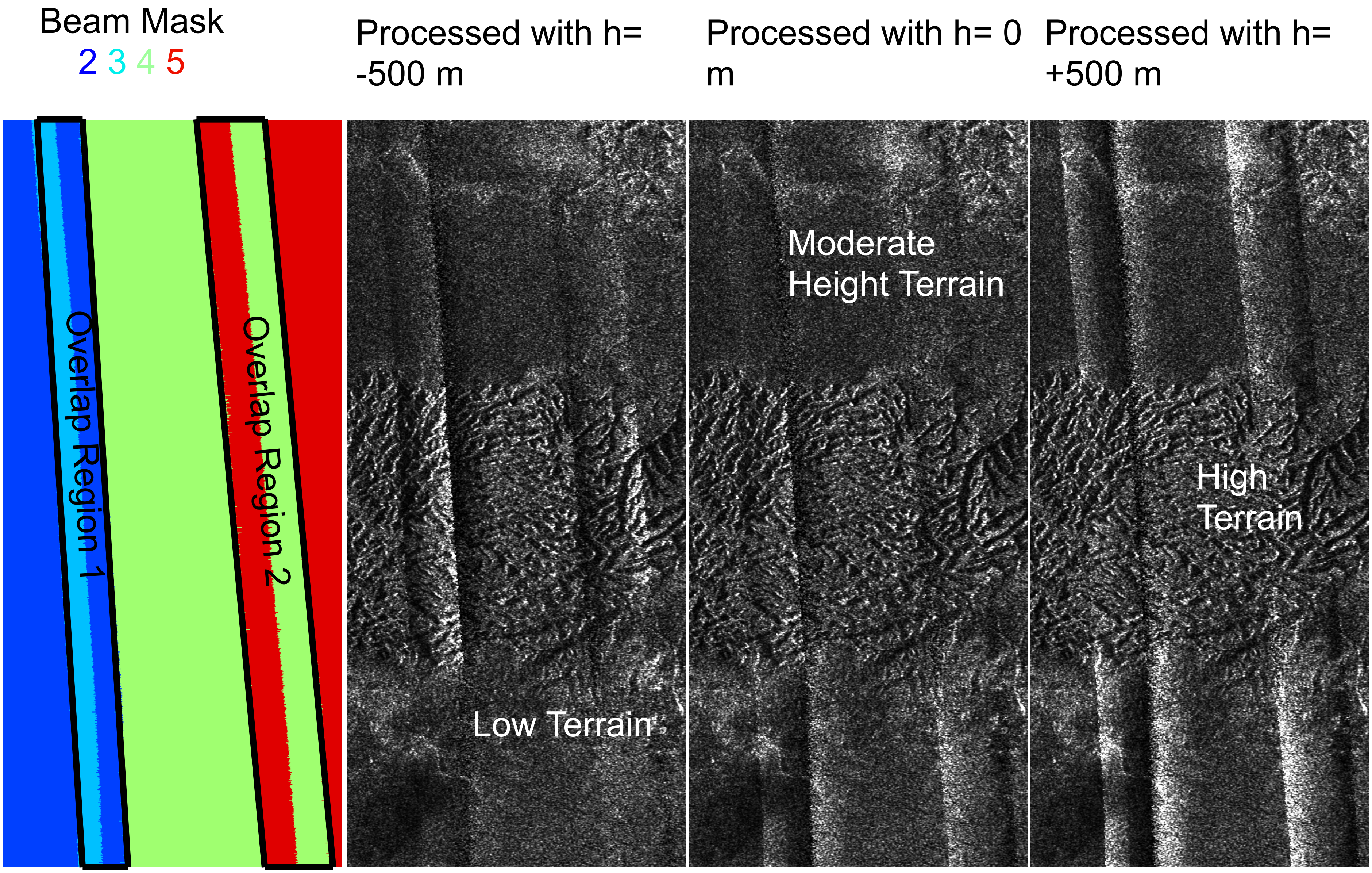


Passive radiometry : Black body emission gives Brightness Temperature
= Emissivity (composition) * Physical Temperature



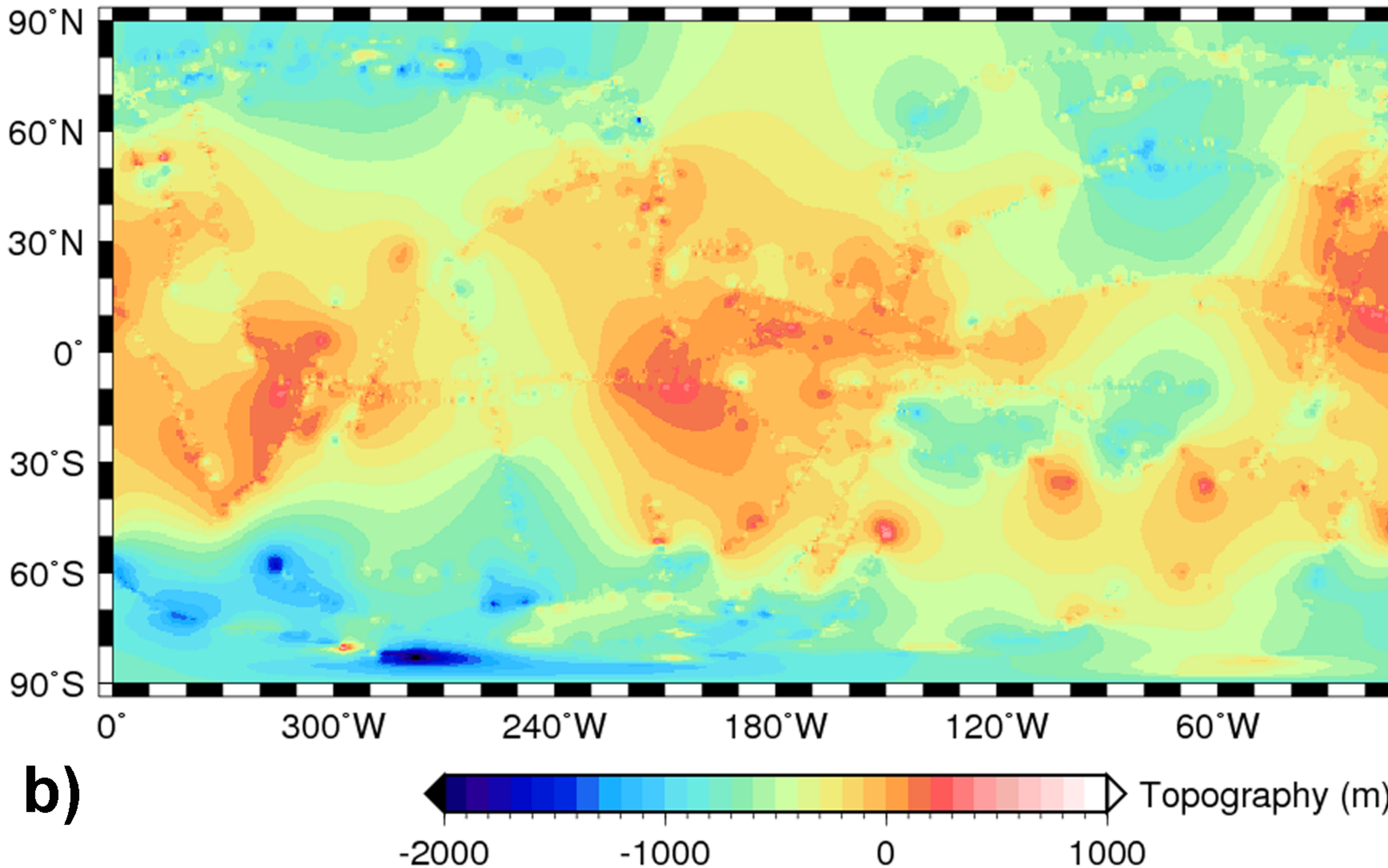
Flyby mission - irregular coverage (now about 40%). Overlaps give stereo, change detection (seas), and constrain rotation state of Titan

SAR Topo – monopulse amplitude matching across seams

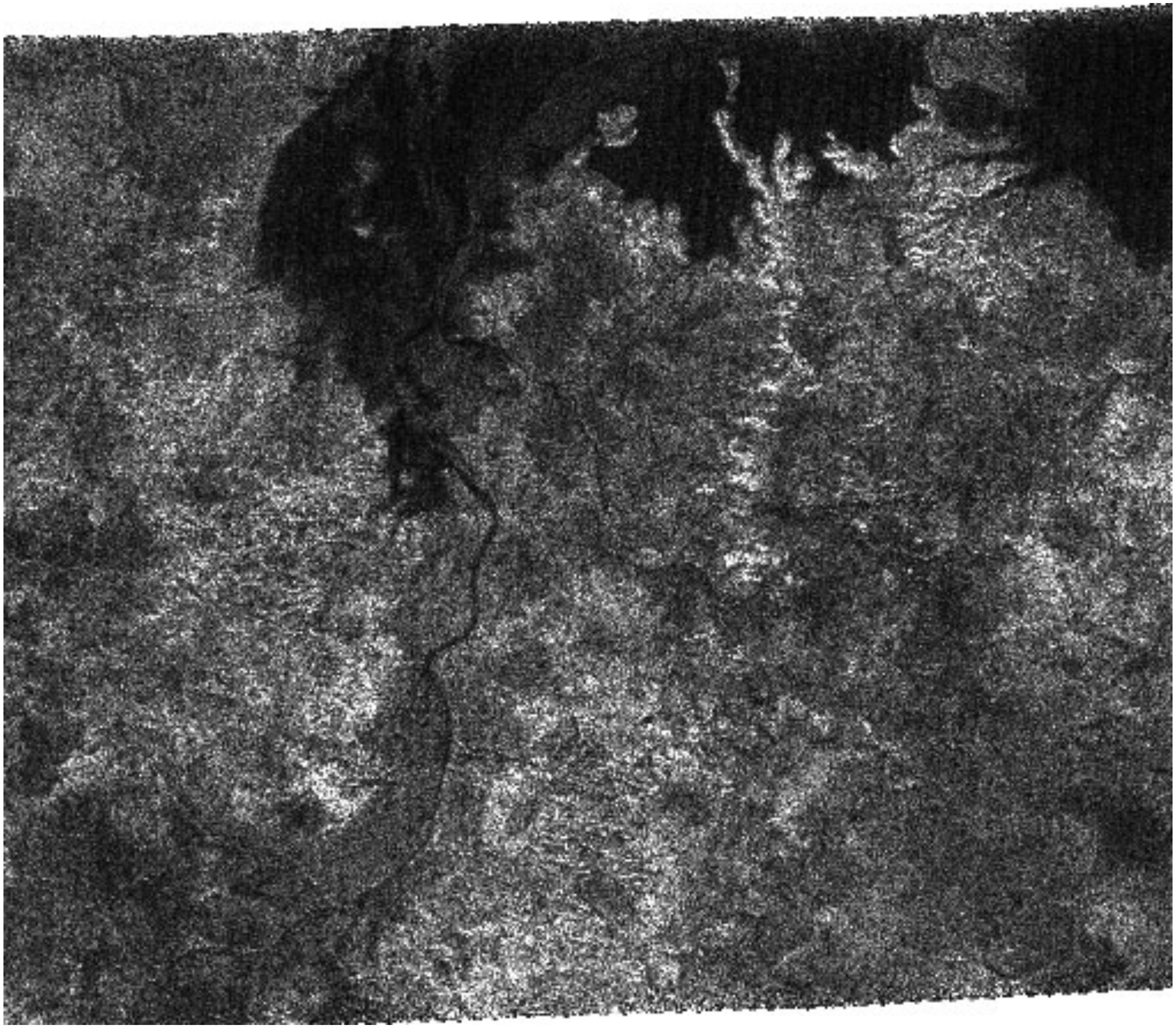


Dark to light band in Overlap Region indicates height underestimation, Light to Dark overestimation. Ignore Banding outside of overlap regions.

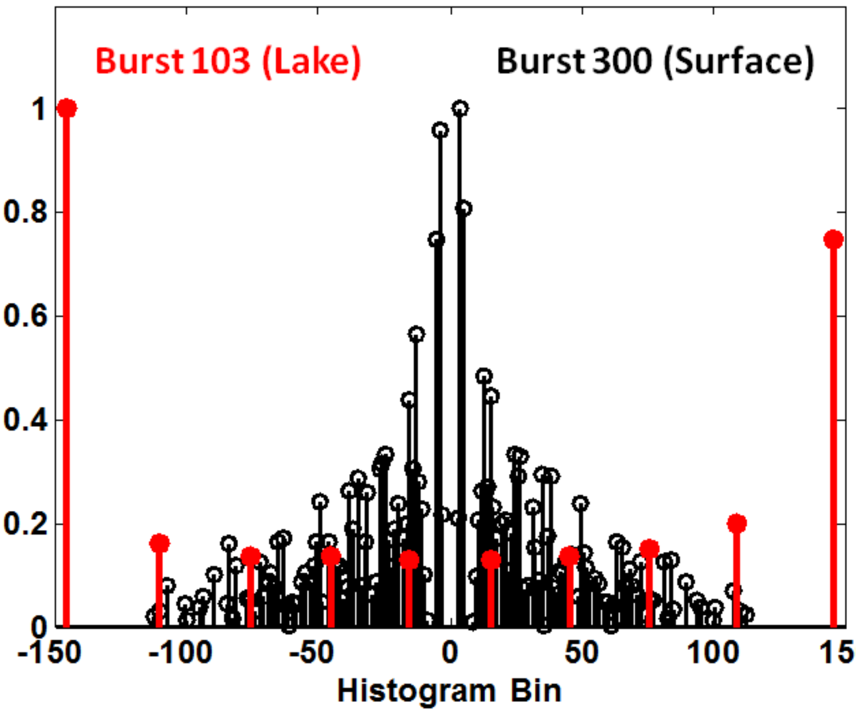
~10% of 1x1 degree bins populated by data – allows global spline-interpolated topography map - Lorenz, Icarus, 2013



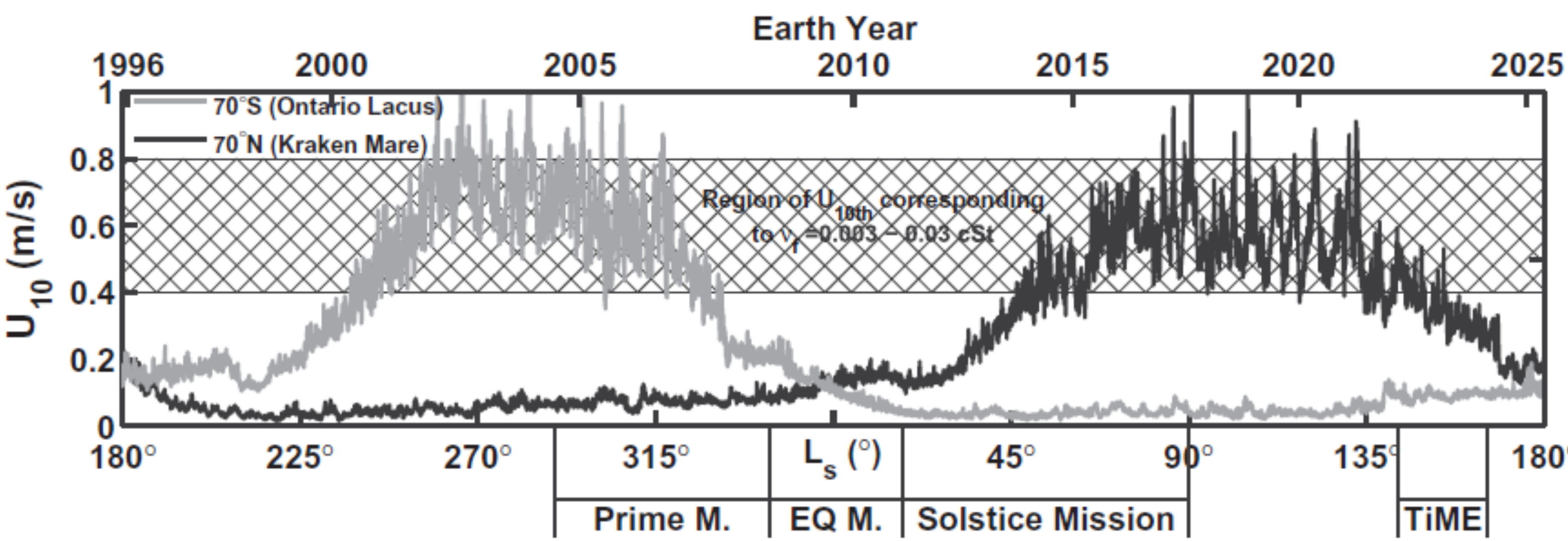
b)

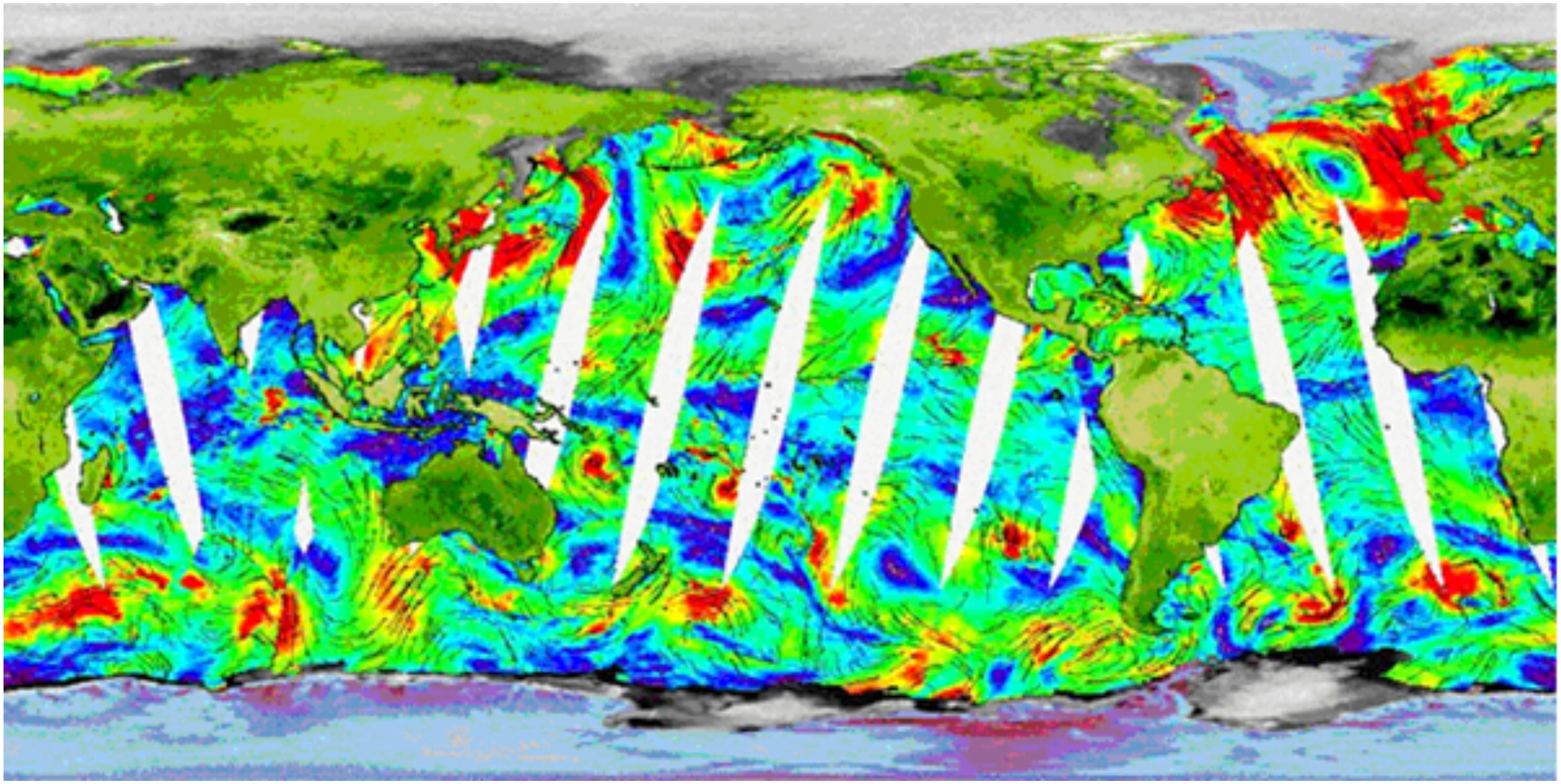


Darkest regions seen so far are in Titan's arctic (>74^{o}N) – apparently lakes that are presently-filled with liquid – dark channels flow into or between several.

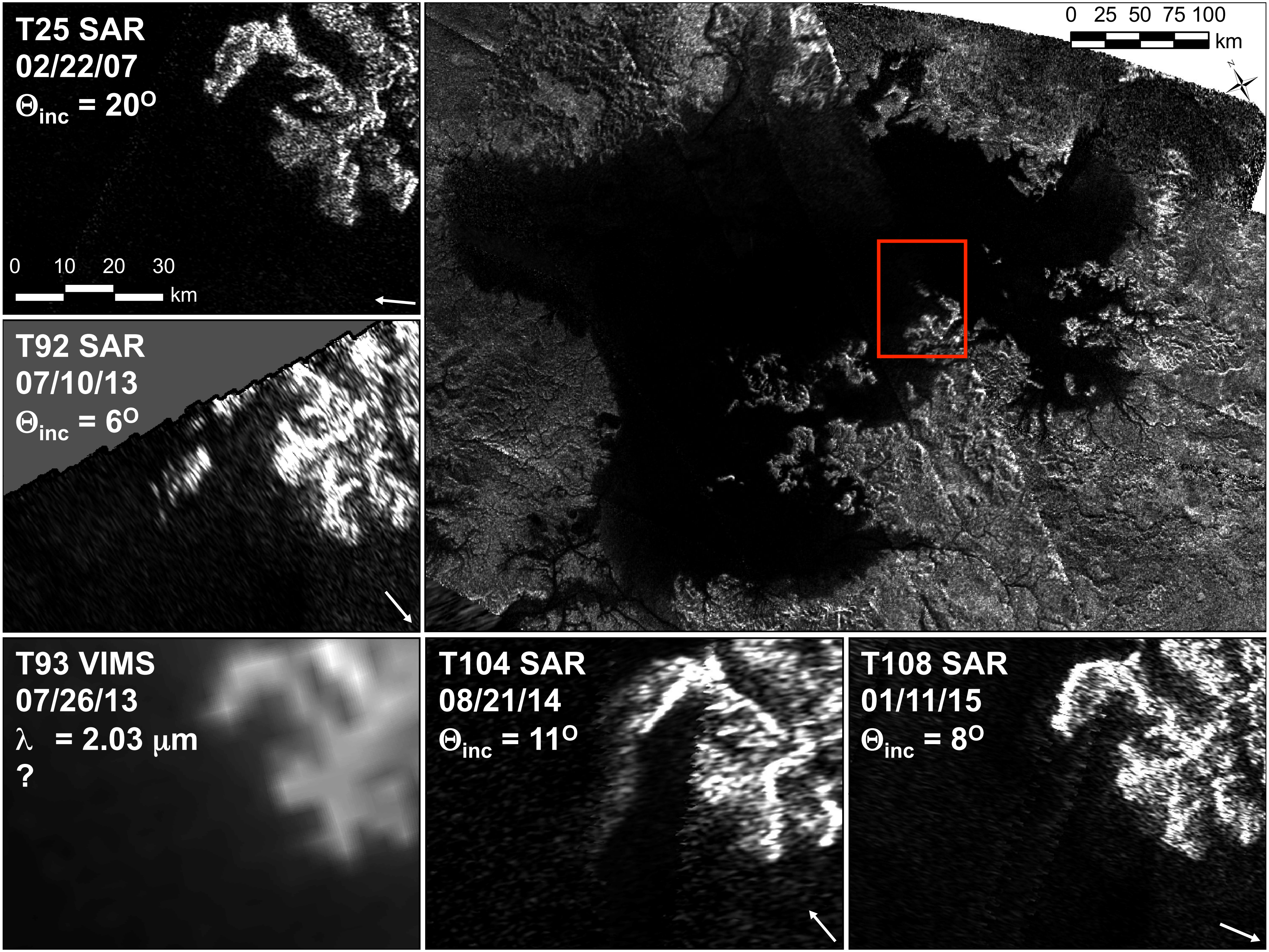


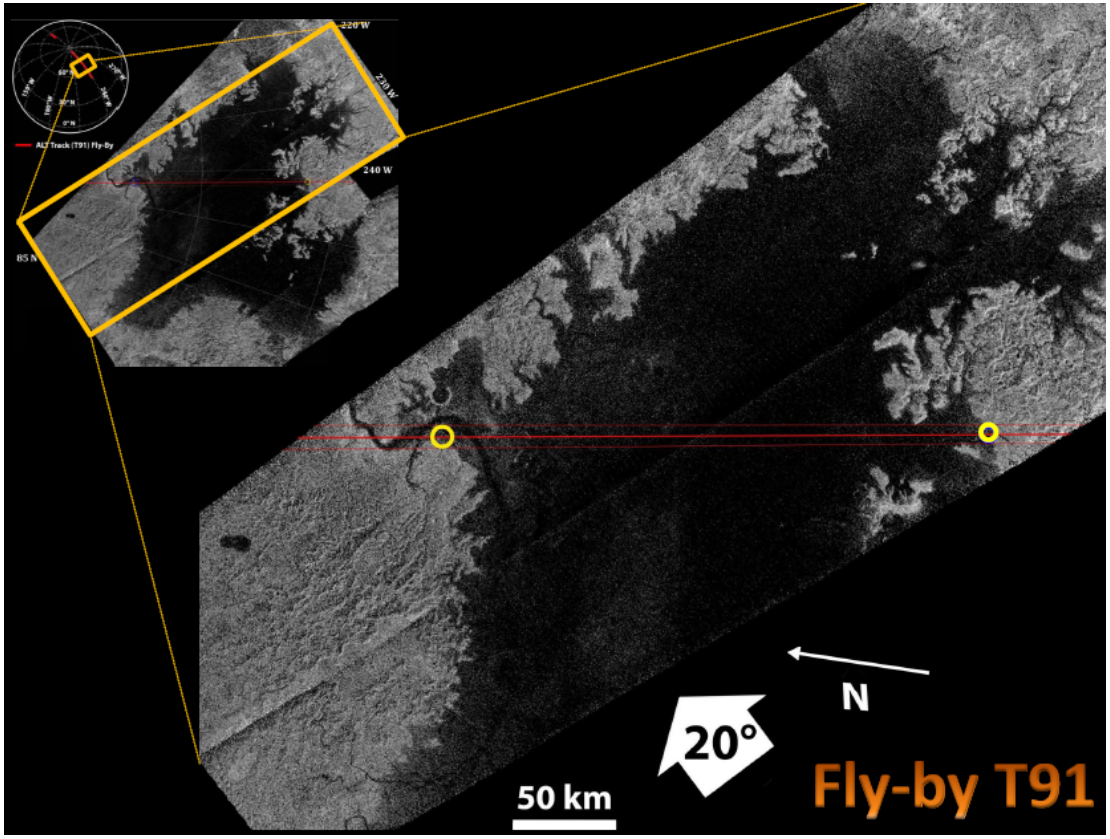
Echo samples show non-Gaussian character over Ontario (Wye et al., GRL, 2009)
Rather than typical incoherent sum from echoes with random ranges (phases) most of the echo power is coherent (mirror image of outgoing chirp) – has saddle-shape histogram. All the energy is coming from specular reflection within the Fresnel zone (radar ‘selfie’) implies rms surface roughness <3mm !
Also true of Ligeia on T91. But northern winds picking up into summer ?

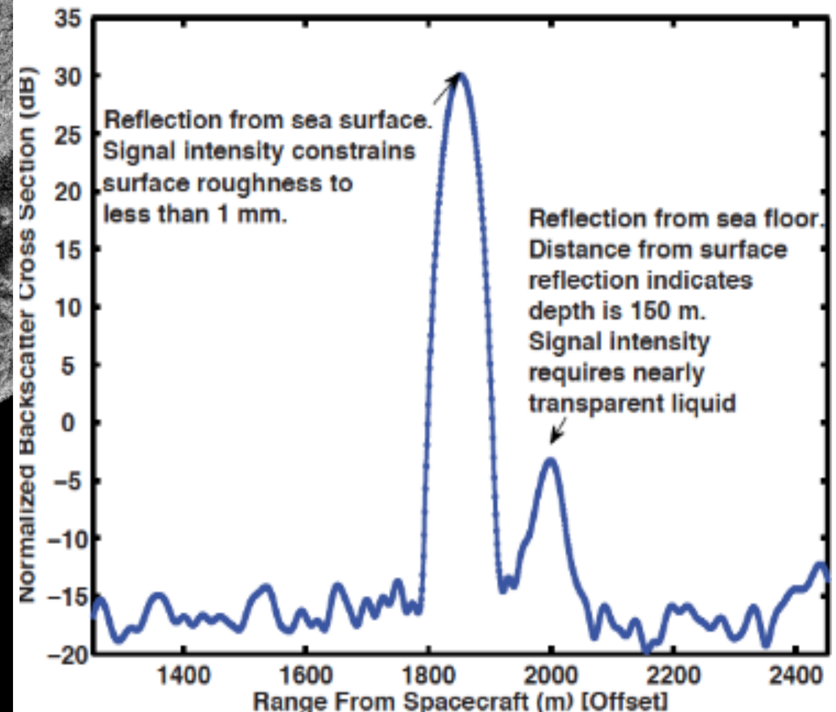


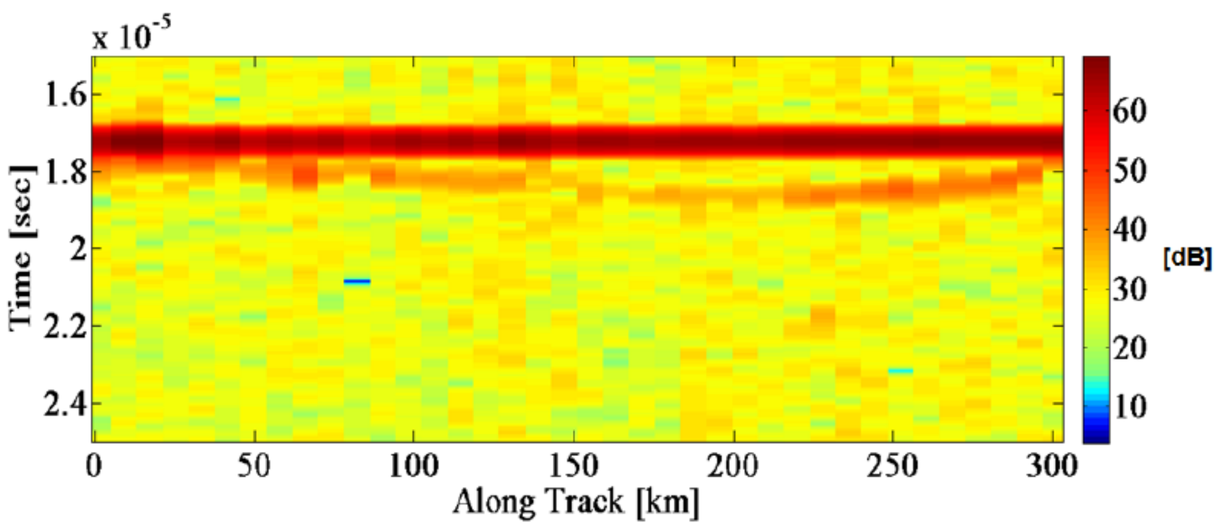


Scatterometry routinely used to measure sea-state (and thereby infer sea-surface winds) over much of Earth. Important input into weather models, as few stations over many ocean areas

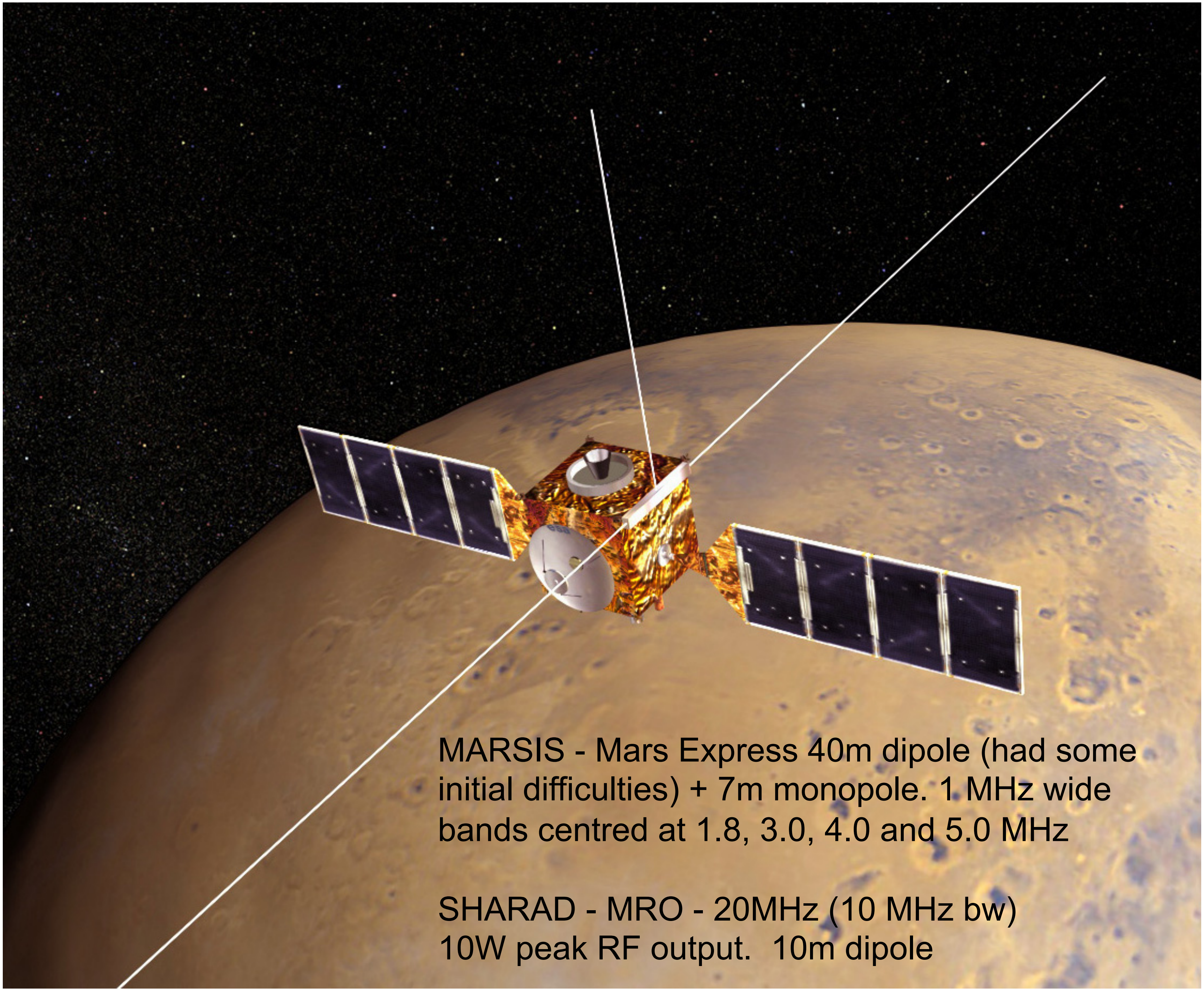

T25 SAR
02/22/07
Θ_{inc} = 20°
0 10 20 30 km
T92 SAR
07/10/13
Θ_{inc} = 6°
T93 VIMS
07/26/13
λ = 2.03 μm
?
T104 SAR
08/21/14
Θ_{inc} = 11°
T108 SAR
01/11/15
Θ_{inc} = 8°
0 25 50 75 100 km

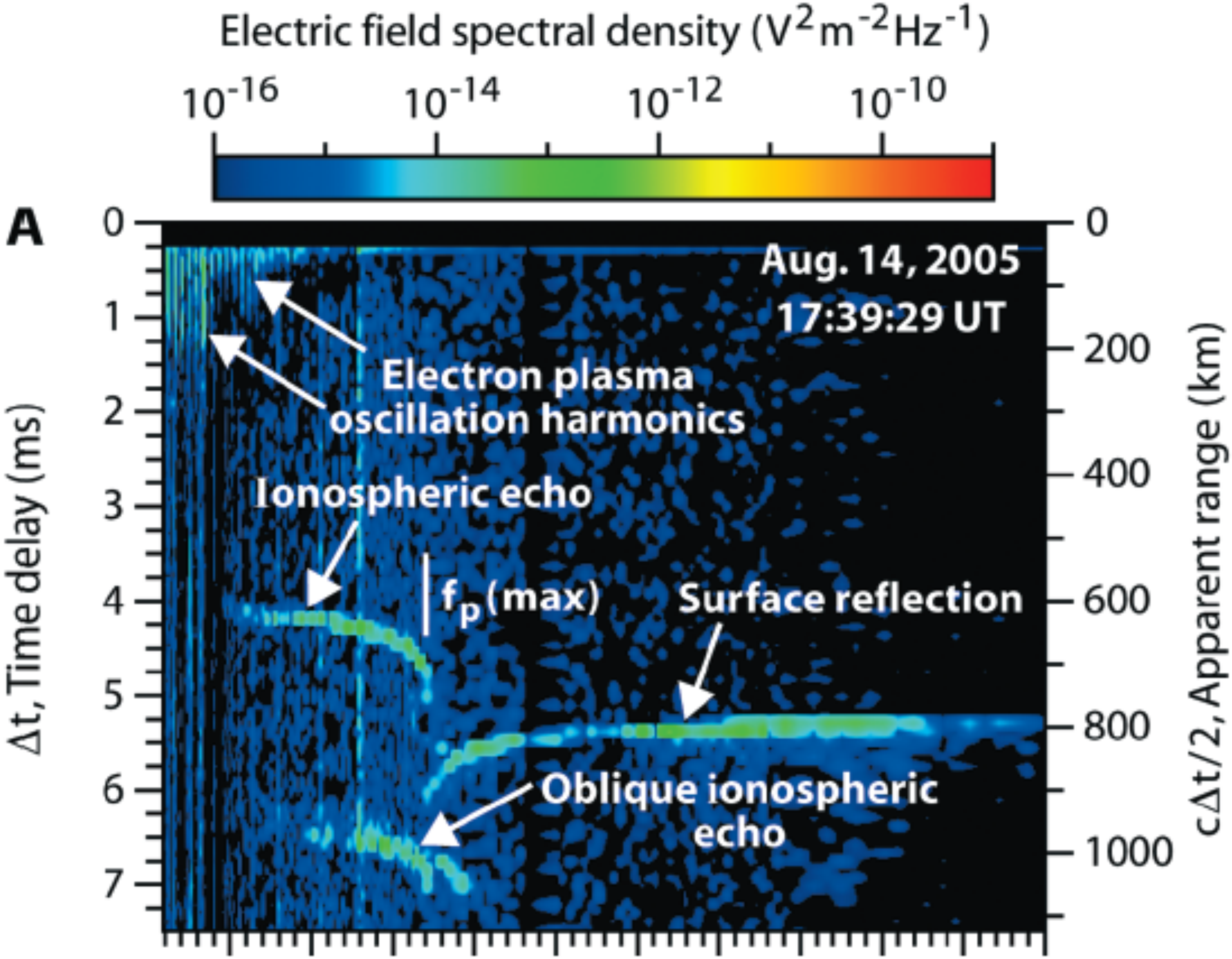




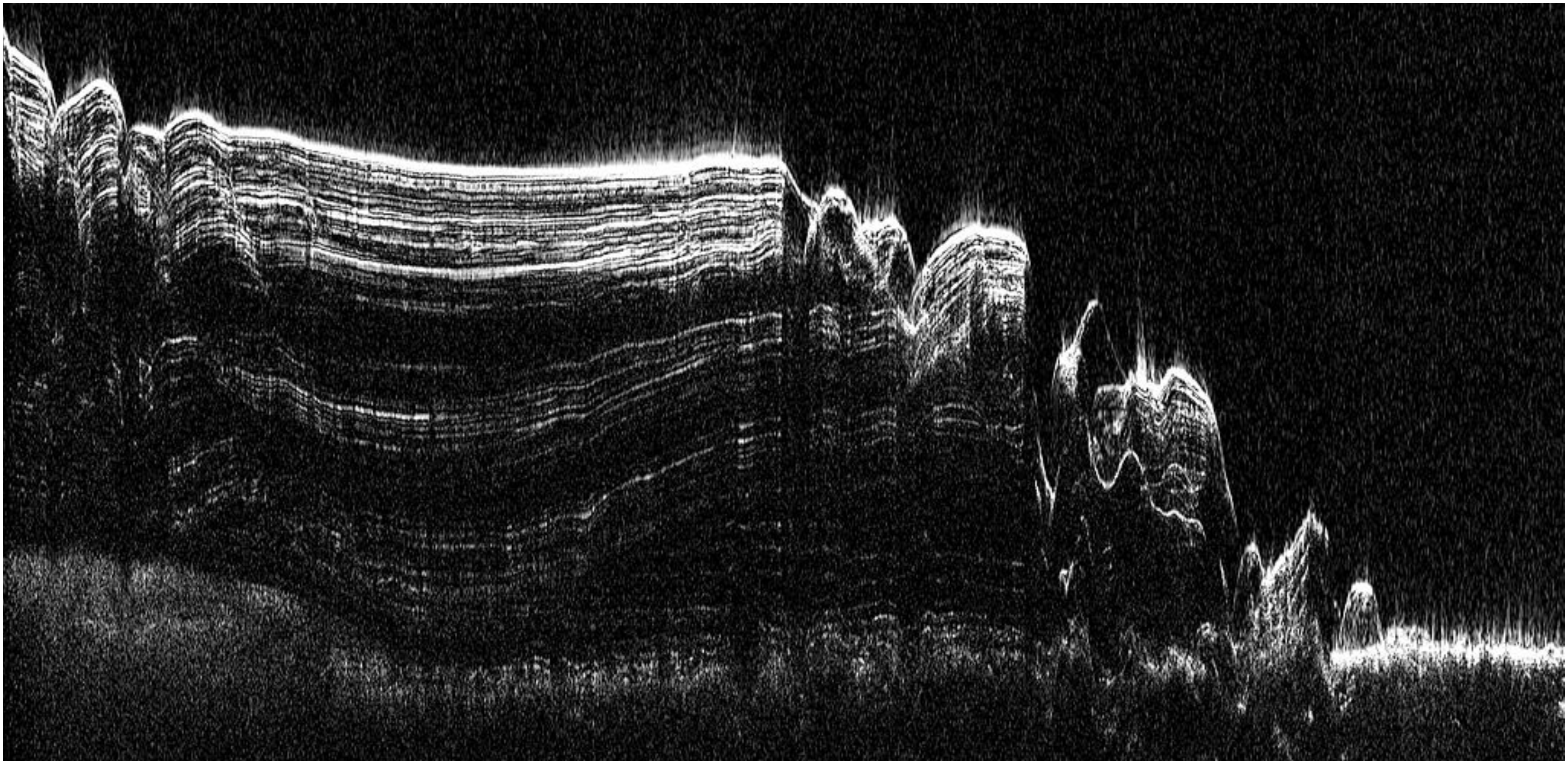


Unexpected radar-transparency of Ligeia Mare allowed detection of bottom echo in T91 altimetry. Bottom is ~160m down. Indirectly implies ‘clean’ (methane-rich) composition Mastrogiuseppe et al., GRL, 2014. Radiometry – see Le Gall talk GP3 Wednesday)

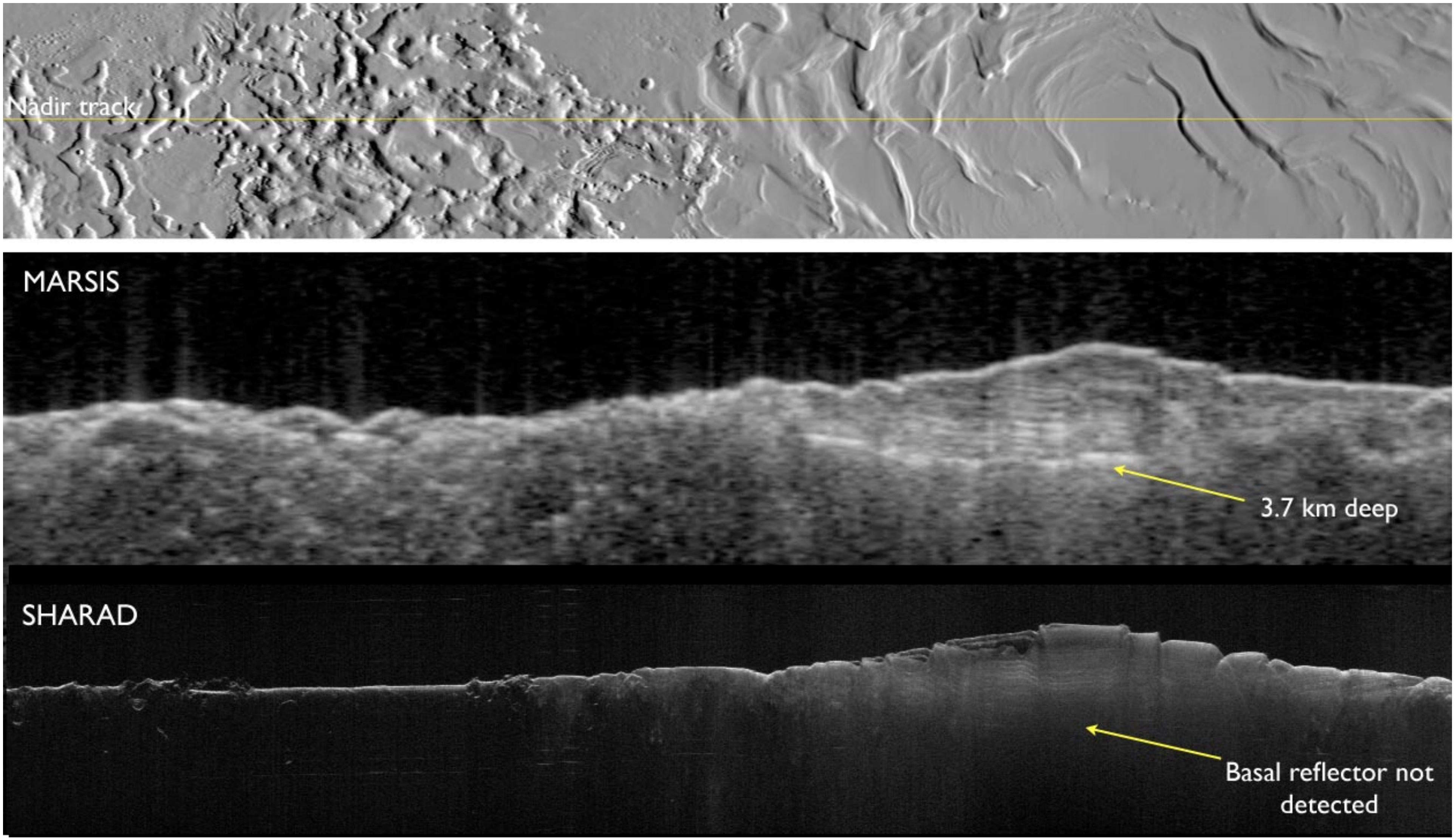

MARSIS - Mars Express 40m dipole (had some
initial difficulties) + 7m monopole. 1 MHz wide
bands centred at 1.8, 3.0, 4.0 and 5.0 MHz
SHARAD - MRO - 20MHz (10 MHz bw)
10W peak RF output. 10m dipole



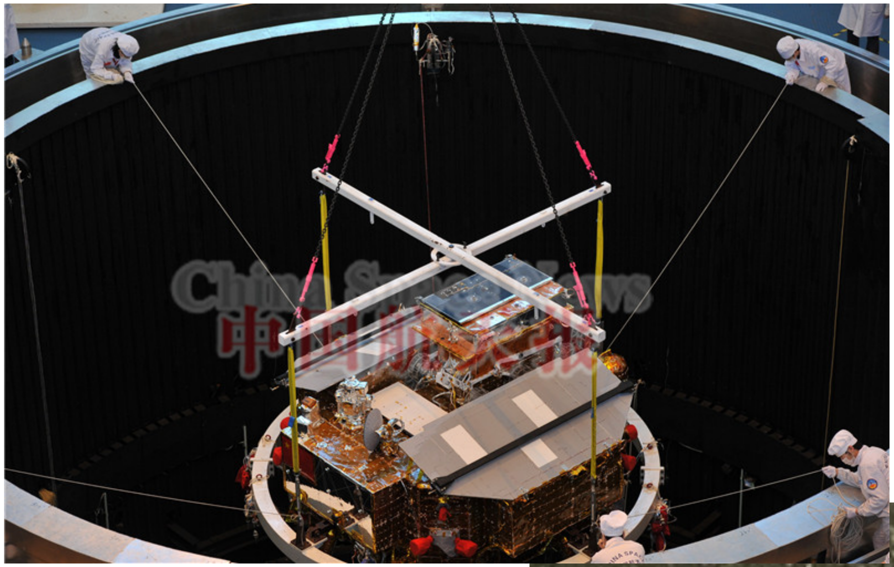
Electric field spectral density ($V^2 m^{-2} Hz^{-1}$)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
A
Aug. 14, 2005
17:39:29 UT
Electron plasma oscillation harmonics
Ionospheric echo
f_p(max)
Surface reflection
Oblique ionospheric echo
Δt, Time delay (ms)
0
1
2
3
4
5
6
7
$c\Delta t/2$, Apparent range (km)
0
200
400
600
800
1000

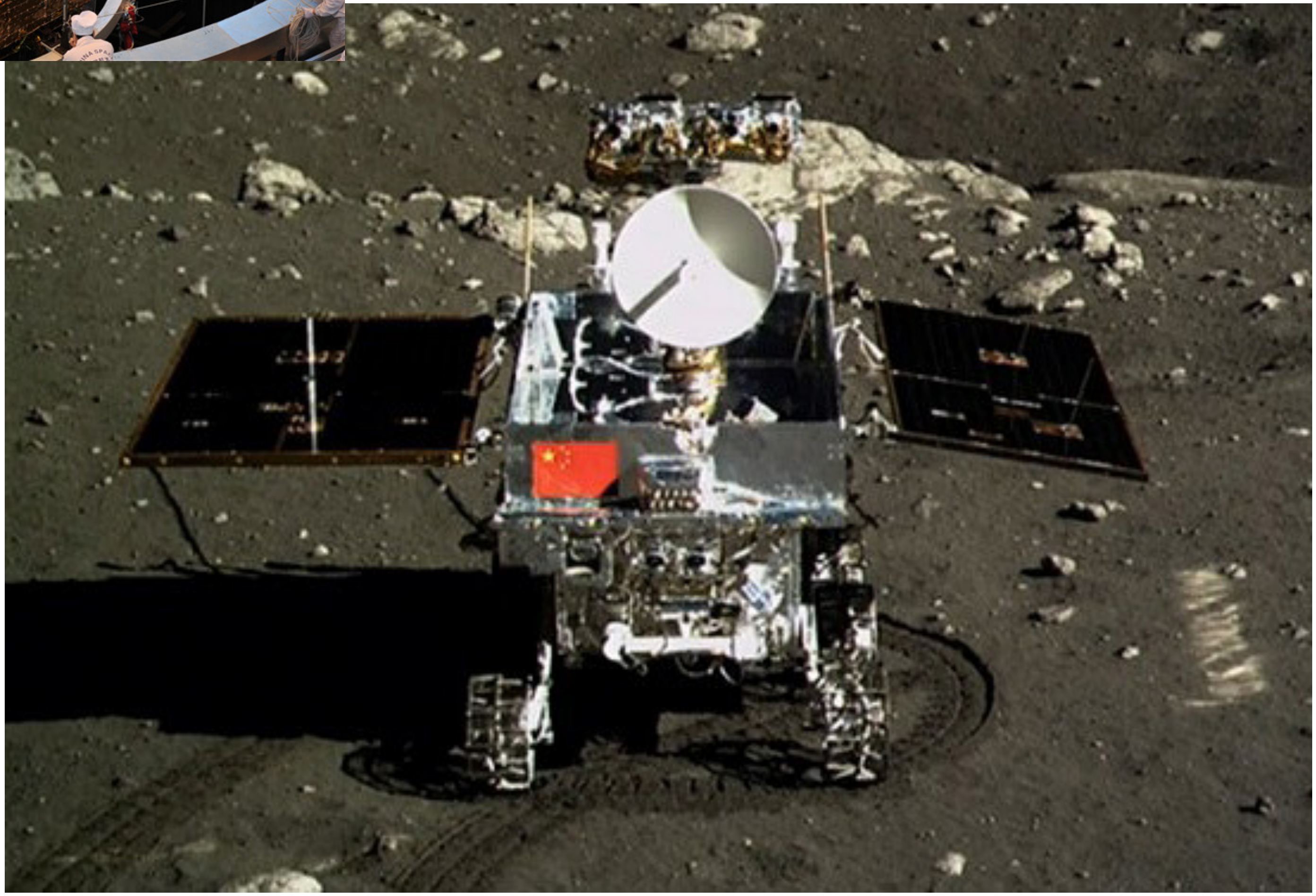


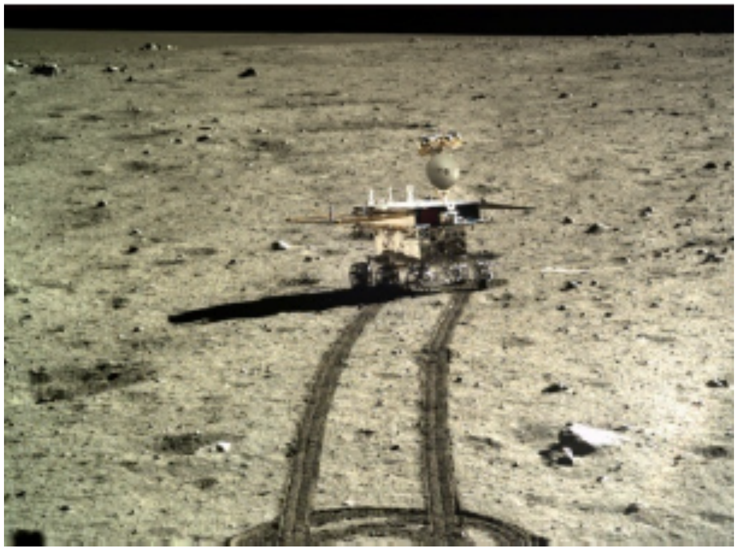
SHARAD radargram, showing fine detail of layers in the Martian north polar cap.
Ice is relatively clean (hence transparent)

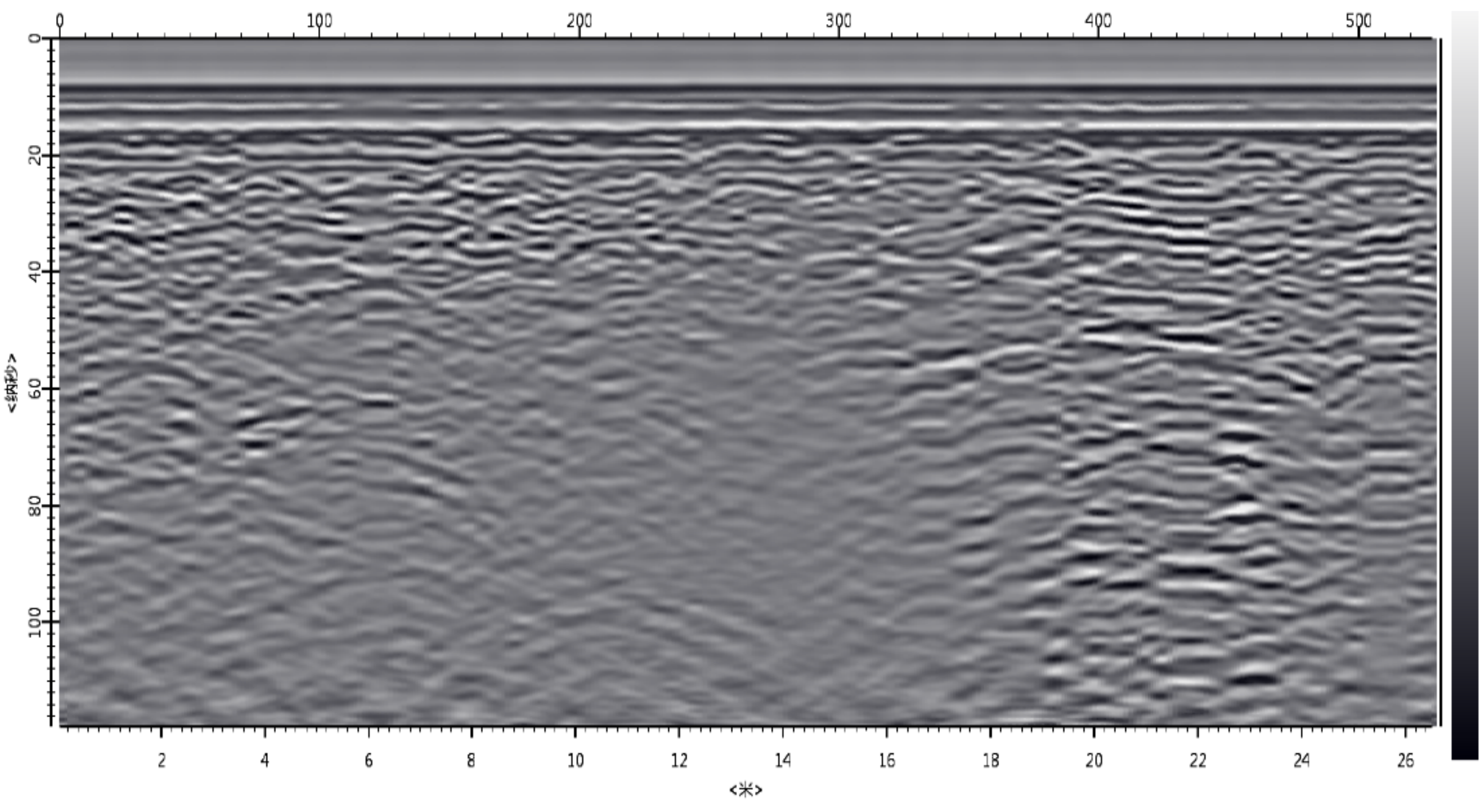


South Polar Layered Terrain.   Shorter wavelength SHARAD data are sharper (shorter wavelength = higher resolution) but does not penetrate to depth (generally only science results portrayed are those from the polar caps..)









0
100
200
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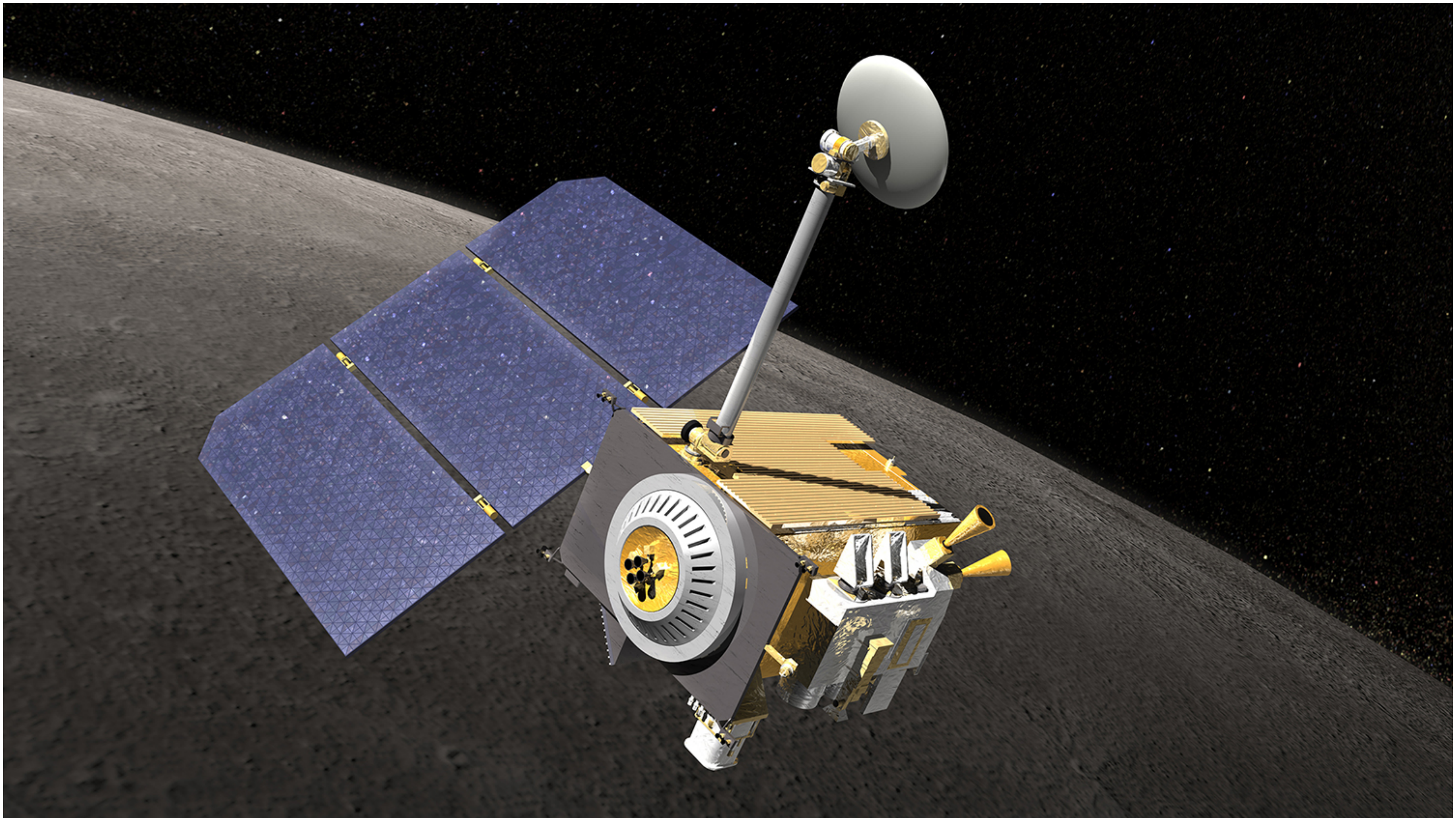
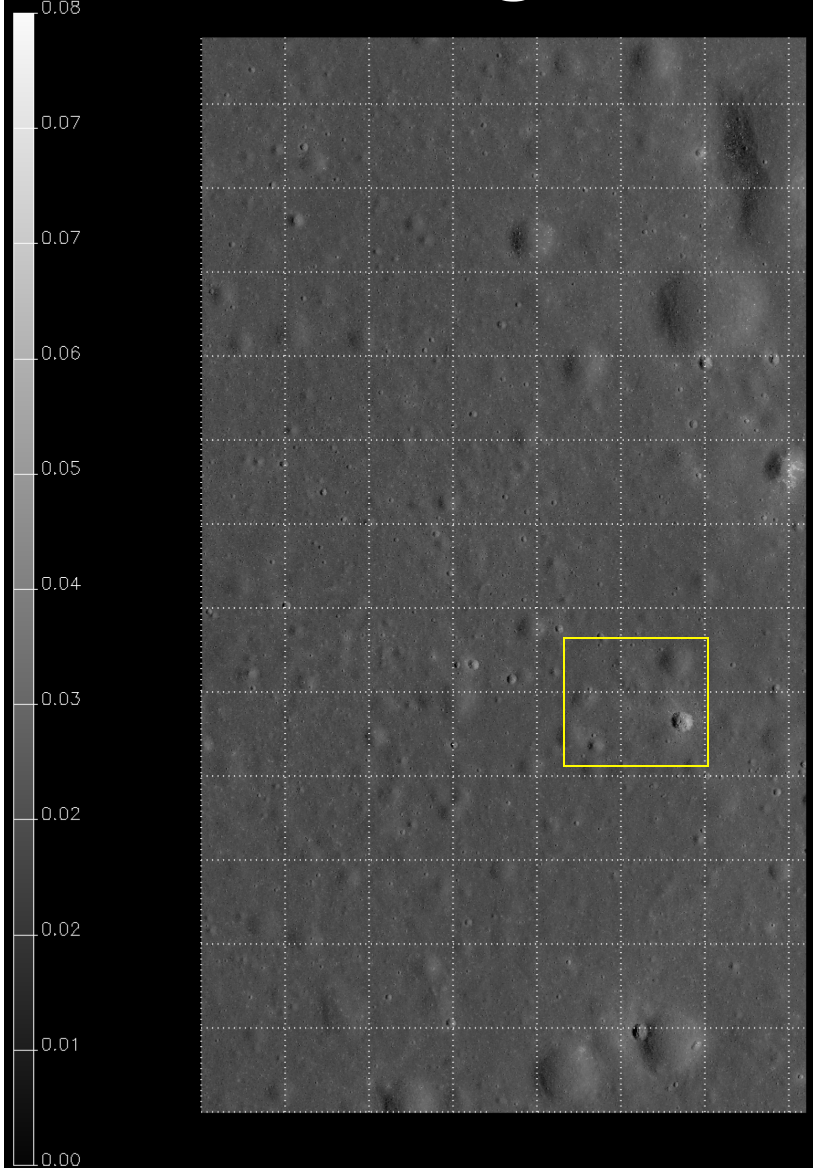
Mini-RF/ Mini-SAR New Lightweight SARs to the moon
Chandrayaan-1 (ISRO) 2008-2009
Lunar Reconnaissance Orbiter (NASA) 2009-

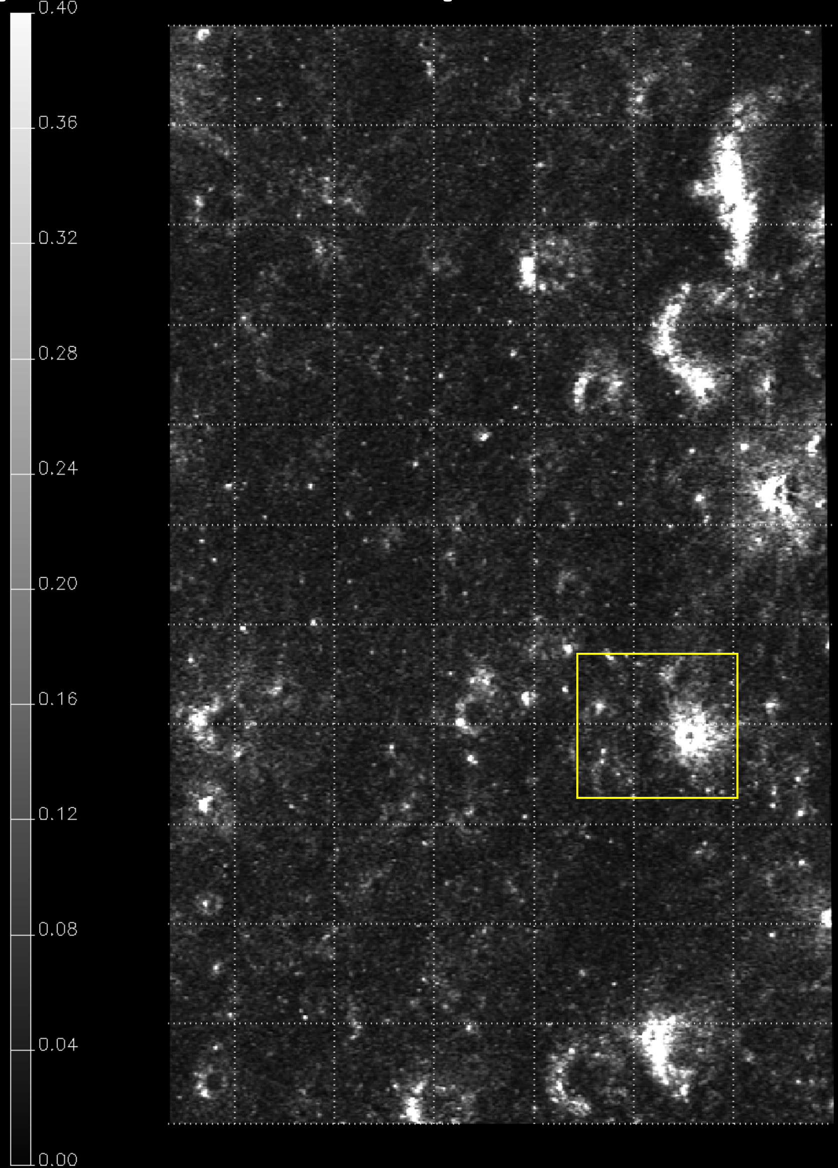


Johns Hopkins University Applied Physics Laboratory, US Naval Air Warfare Center, Sandia National Laboratories, Raytheon and Northrop Grumman
Mini-SAR on Chandrayaan-1 (S-band only) ~9 kilograms
Mini-RF instrument on the Lunar Reconnaissance Orbiter (S-band and X-band) ~14 kilograms. Polarimetric SAR

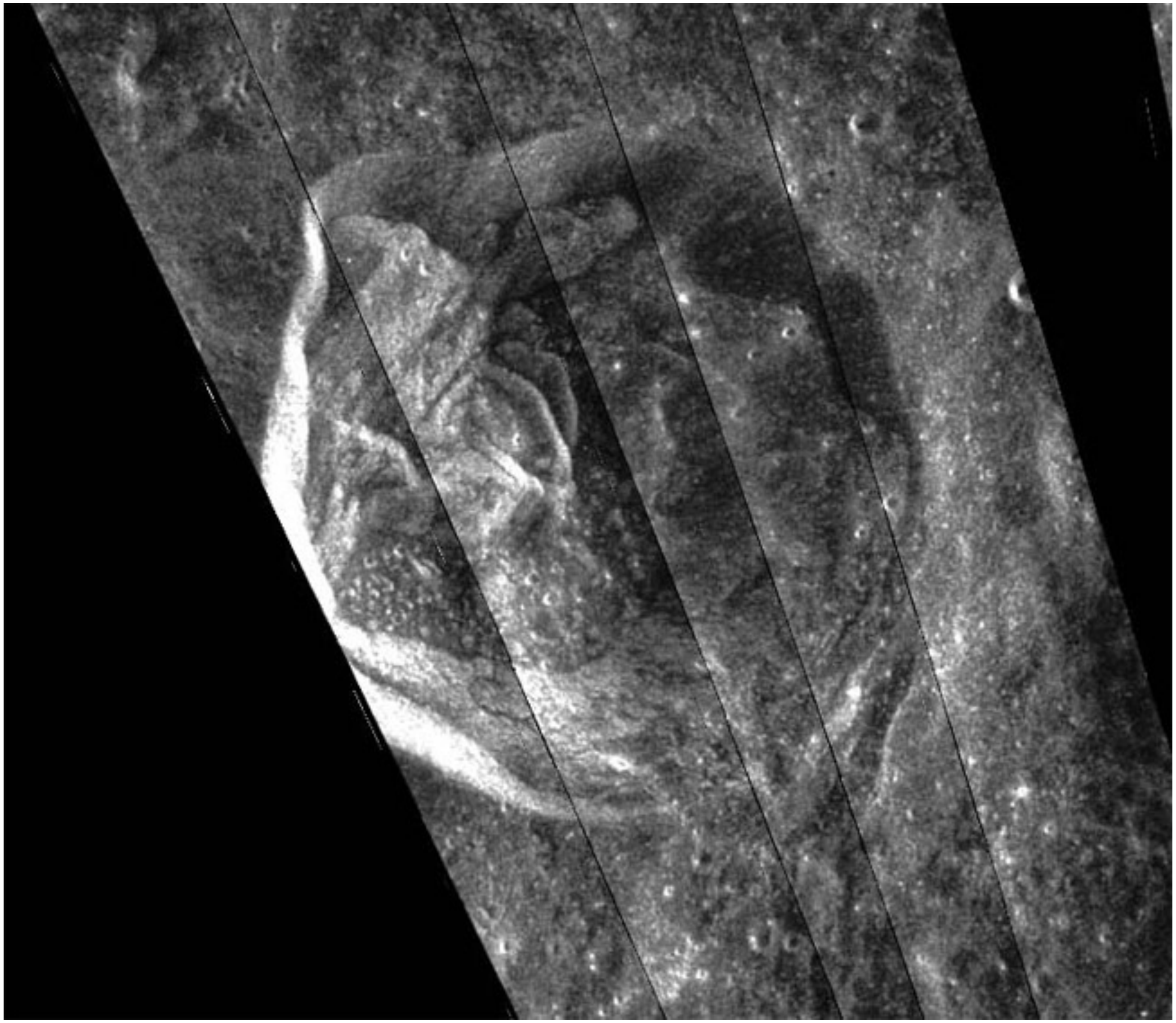
LRO Regional Perspective - Apollo 11



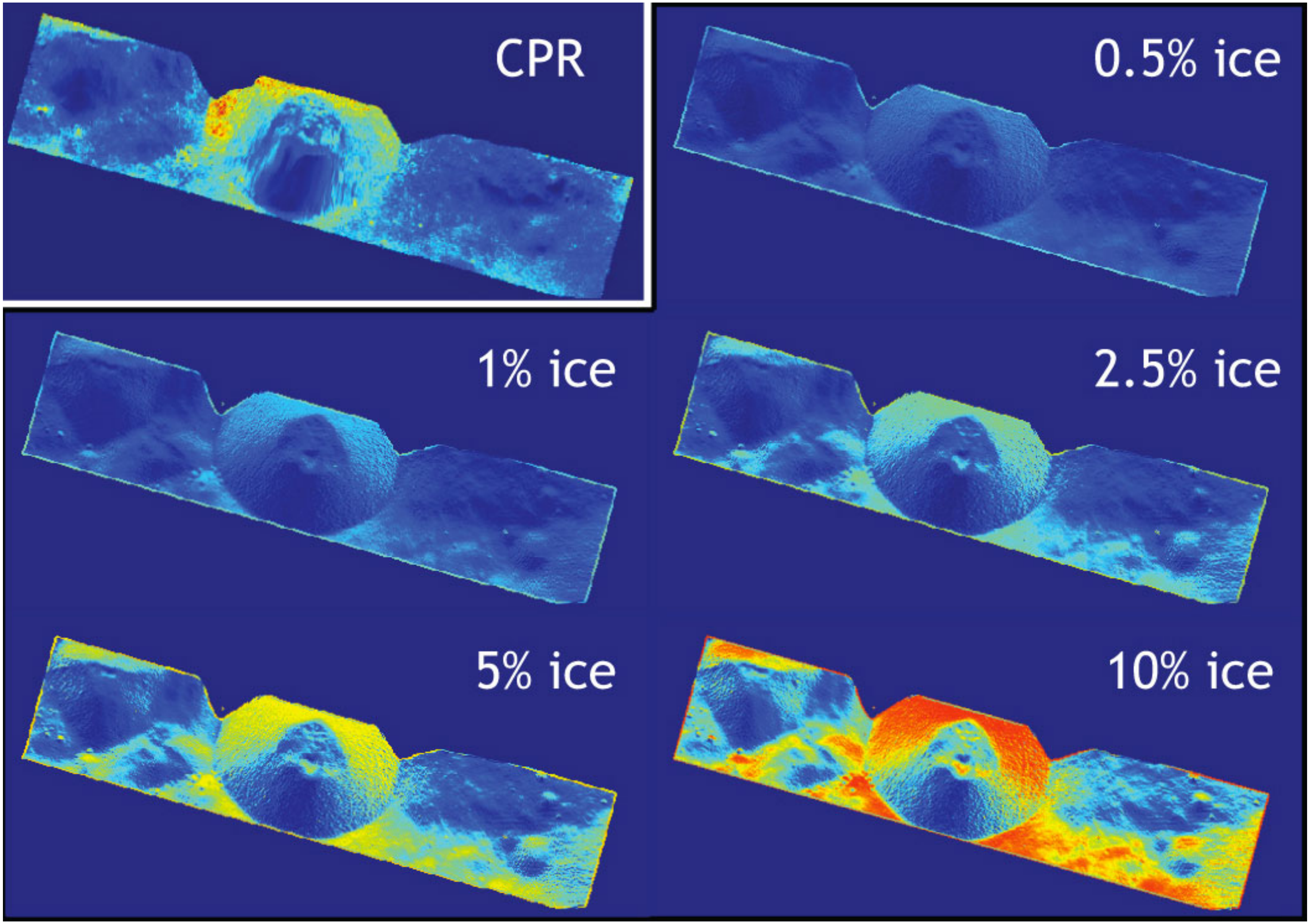
Apollo 11 – LROC (NAC)

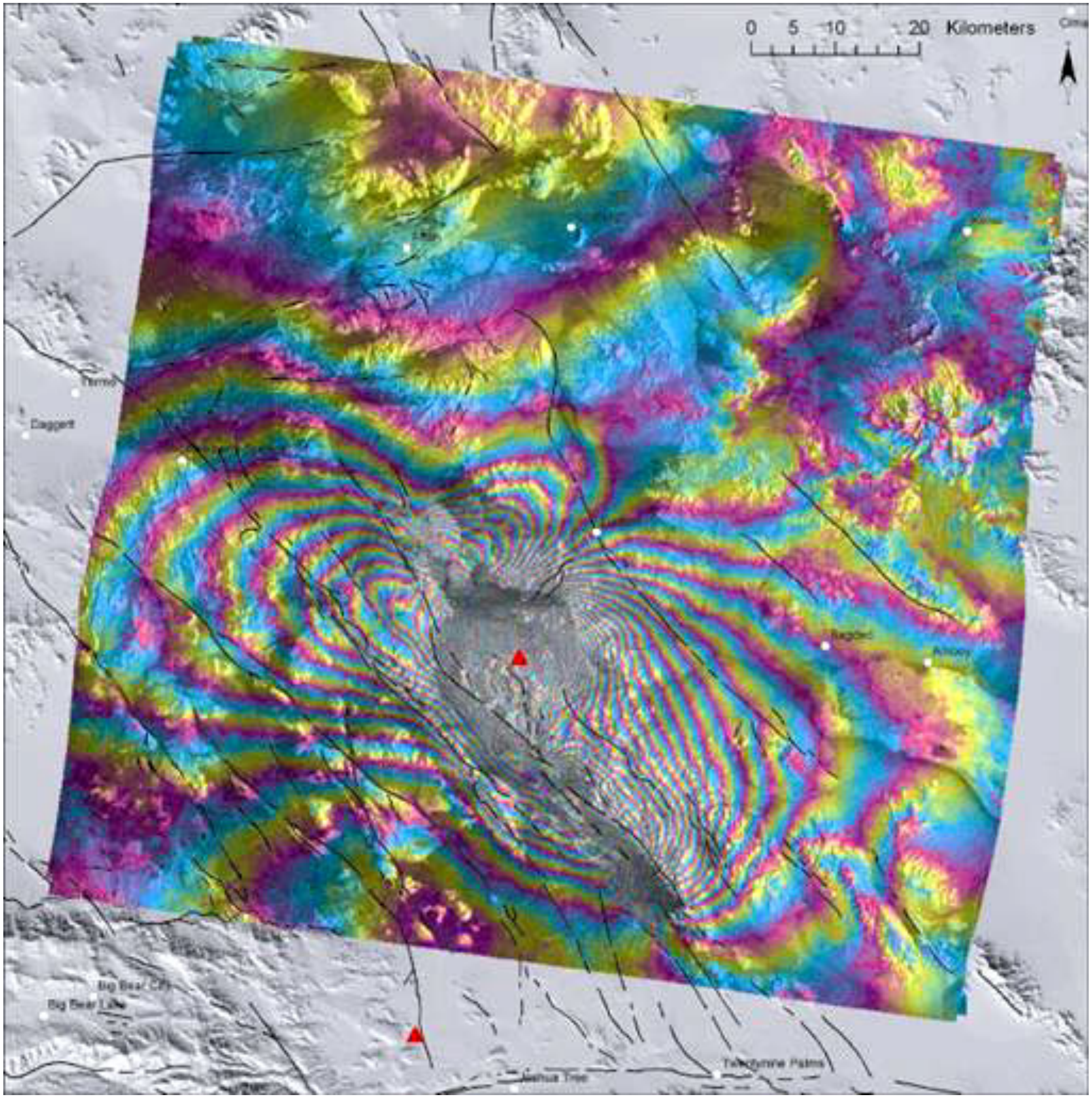


Apollo 11 Mini–RF – Stokes Parameter (S1)



Rozhdestvensky K is a moderately sized (42-kilometer [26-mile] diameter) impact crater on the southern rim of the larger crater Rozhdestvensky, near the moon’s north pole. These Mini-SAR images show massive slumping, as result of wall collapse caused by gravity. These images demonstrate that Mini-SAR images will be of great value in deciphering the geological evolution of the moon. Credit: ISRO/NASA/JHUAPL/LPI


CPR
0.5% ice
1% ice
2.5% ice
5% ice
10% ice



0 5 10 20 Kilometers
Daggett
Big Bear City
Big Bear Lake
Joshua Tree
Twentynine Palms

Planetary Radars

Much of what we know about the surface of Titan has been obtained by radar.

Almost all of what we know about the surface of Venus has been obtained by radar.

Provide data on roughness at lander-relevant scales (landing site certification). Also provide access to subsurface and the planet's history

A rich array of techniques to address different questions. Radars come in all shapes and sizes (don't assume they are big/heavy/power hungry – just depends : planetary mission energy requirements usually driven by downlink data energy demand)

Things to look forward to –
Ice-penetrating radar at Ganymede/Europa (maybe one day Titan?)
Back to Venus with high-resolution imaging and controlled altimetry network?
Interferometry ?